ELEMENTARY AERONAUTICS

A. P. THURSTON

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OR

THE SCIENCE AND PRACTICE OF AERIAL MACHINES.

BY

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PREFACE.

THE author has been persuaded to publish this work in the hope that it may be useful in leading others to the scientific study of aeronautics.

The aim of the author, therefore, has been to present to the reader a simple and concise account of the action of air upon moving planes, aerocurves, propellers, bars and the like, and the application of these principles to practice.

The theory of the normal and inclined plane and aerocurve is dealt with in Chapters I. and II.

An introduction to the important problem of stability has been given in Chapters III. and IV. The theories and results deduced in Chapters III. and IV. appear largely to have been confirmed by various experimenters and scientists since these conclusions were arrived at.

The theory of the propeller and helicopter, and the calculations relating to the design of a flying machine, are set out in Chapters V., VI. and VII.

The principal instruments and apparatus used in an aeronautical laboratory are described in Chapter VIII., and the rest of the book is devoted to a description of the chief types of flying machines and engines.

The author's thanks are due to the Editors of the *Aeronautical Journal* and of *Aeronautics* for the loan of blocks, and to his friends, Messrs S. E. R. Starling, B.Sc., and T. Kimpton, for kindly reading the proofs.

Most of the illustrations have been specially prepared, and the author desires to acknowledge his great indebtedness to Messrs T. Kimpton and H. K. Pettet for valuable help in the preparation of two or three drawings.

A. P. T.

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CHAPTER I

THE atmosphere, "the sphere of vapour" which envelops the earth, and which is commonly called air, has become of increased importance and interest to man, since the discovery of the flying machine has made it the highway of the future.

The density of the air is at its maximum at the earth's surface, and rapidly decreases as the altitude increases; thus, at about $3\frac{1}{2}$ miles the density is only one-half, and at 7 miles one-third of that at sea-level.

The height to which the earth's atmosphere extends is not known with certainty, but it may be safely stated to be not less than 50 miles. At this height the air is extremely rarefied, being about 25,000 times more rarefied than at sea-level.

Air is nearly 800 times lighter than water: one cubic foot of dry air at sea-level weighing about 1·29 ozs. or 0·08 lbs.

It is with this light and subtle fluid, with its varying currents and eddies, that we have to deal in the study of aeronautics.

THE NORMAL PLANE

If a plane is placed at right angles, or normal to a current of moving air, the air will strike the plane and will exert a force upon it. If the velocity of the air is doubled, then twice as much air will strike the plane every second, and, since the velocity is doubled, every particle will strike with double the force; thus, the total force acting on the normal plane will be four times as great.

Now, if the speed is tripled, then three times the amount of air will strike the plane every second, and every particle will strike with three times the force; thus, the total force acting on the plane will be increased to three times three, that is nine times.

Therefore, from theoretical reasons, we find that the resistance of air to a normal plane varies as the square of the velocity.

In the case of a current of air striking a normal plane, the conditions are not so simple as we have assumed. It will be seen from Figs. 23, 24 that some of the air in the

FIG. 1.—Maxim's Machine, No. 2.

centre of the plane strikes dead on, and that the air at the sides is deflected; also that the air passing over the sides drags away some of the air from the back and creates a rarefaction which is generally spoken of as a suction.

It has been found, as the result of many experiments,

that *the resistance of a normal plane varies as the square of the velocity.* Thus we may write:

Resistance $= KAV^2$. Where $K =$ constant.
$A =$ area of plane.

At very high speeds, the resistance increases at a greater rate than the square of the velocity, until a maximum is reached at about the velocity of sound, viz., 1100 ft. per sec., or 750 miles per hour, when the resistance varies as the fifth power of the velocity. At higher speeds than the velocity of sound, the resistance decreases.

The following values of n are given by Major Squiers. Where n is the index of the velocity in the equation, $P = KAV^n$.

n	Velocity	
	Feet per sec.	Miles per hour
2	Less than 790	Less than 592
3	Between 790 and 970	Between 592 and 639
5	„ 970 and 1230	„ 639 and 836
3	„ 1230 and 1370	„ 836 and 934
2	„ 1370 and 1800	„ 934 and 1227
1·7	„ 1800 and 2600	„ 1227 and 1773
1·5	Greater than 2600	Greater than 1773

There have been very many and various determinations of the constant or coefficient K.

The following table gives a few values, the velocity being taken in miles per hour.

	K=
Renard	·0035
Langley	·0039 to ·00326
Dines	·0029
Stanton	·0027 small planes; ·00318 to ·00322 large planes
Eiffel	·003

The value ·003 has been generally accepted as the best all-round value for K.

∴ Resistance on a normal plane in lbs. = P 90 = ·003 AV^2
Where A = area in sq. feet;
V = velocity in miles per hour.

SPEEDS AND PRESSURES

(NORMAL PLANE)

Miles per hour	Feet per sec.	Metres per sec.	Lbs. per sq. foot
1	1·47	·447	·003
2	2·93	·894	·012
3	4·41	1·341	·027
4	5·87	1·783	·048
5	7·33	2·235	·075
6	8·87	2·682	·108
7	10·29	3·138	·147
8	11·76	3·576	·192
9	13·23	4·035	·243
10	14·66	4·470	·300
11	16·12	4·916	·363
12	17·59	5·365	·432
13	19·06	5·813	·507
14	20·53	6·261	·588
15	22·00	6·705	·675
16	23 47	7·158	·768
17	24·94	7·601	·867
18	26·41	8·050	·972
19	27·88	8·497	1·083
20	29·35	8·945	1·200
25	36·70	11·376	1·875
30	44·00	13·411	2·700
35	51·32	15·646	3·675
40	58·68	17·881	4·800
45	66 00	20·116	6·075
50	73·34	22·352	7·500
55	80·67	24·588	9·075
60	88·00	26·822	10·800
65	95·29	29·043	12·675
70	102·62	31·292	14·700
75	110·00	33·451	16·875
80	117·28	35·763	19·200
85	124·61	38·007	21·675
90	132·00	40·233	24·300
95	139·27	42·448	27·075
100	146·60	44·704	30·000
110	161·2	49·174	36·3
120	176	53·649	43·2
130	191	58·115	50·7
140	205·3	62·585	58·8
150	220	67·056	67·5

The Inclined Plane

It now remains for us to consider the variation in the pressure on a plane as we incline it in the direction of motion.

Sir Isaac Newton, from theoretical assumptions, obtained an expression in which the pressure varied as $\sin^2 \alpha$ where α = angle of inclination between the plane and the direction of motion. This may be written:

$$P\alpha = P90 \sin^2 \alpha \quad \text{(Newton)}.$$

Where $P\alpha$ = normal pressure on inclined plane at angle α.

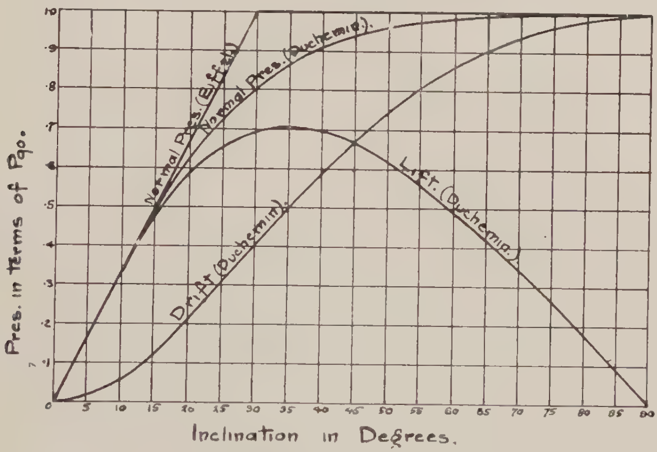


Fig. 2.—Curves of Eiffel Tower and Duchemin formulæ for inclined planes.

Lord Rayleigh showed that the pressure varied more nearly as $\sin \alpha$.

$$P\alpha = P90 \sin \alpha \quad \text{(Rayleigh)}.$$

Colonel Duchemin deduced a formula which appears to agree still more closely with actual practice:—

$$P\alpha = P90 \times \frac{2 \sin \alpha}{1 + \sin^2 \alpha} \quad \text{(Duchemin)}.$$

According to the recent *Eiffel Tower* experiments,

$$P\alpha = \frac{\alpha}{30} \times P90 \quad \text{Up to } 30^\circ$$

$$\text{and } P\alpha = P90 \quad \text{Above } 30^\circ$$

The plotted curves of the Eiffel Tower and Duchemin formulæ are shown in Fig. 2. In the case of the Duchemin formula, the vertical component $P\alpha \cos \alpha$, *i.e.*, "the lift,"

and the horizontal component $P\alpha \sin\alpha$, *i.e.*, "the drift," are also shown plotted.

Fig. 3 shows similar curves obtained by various experimenters. Figs. 31 and 32 also show further curves

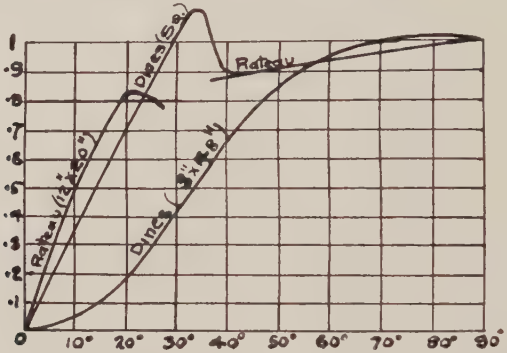


FIG. 3.—Curves for inclined planes. (Dines and Rateau.)

(Rateau) for flat and ship-shaped sections, where curve 1 is the lift, curve 2 is the drift, and curve 3 is the total normal pressure. The pressure F in kilograms for any angle is obtained from the following formula: $F = \phi S v^2$.

Where ϕ is the coefficient read from the diagram and S is the area in square metres.

TABLE OF EQUIVALENT INCLINATIONS

Rise	Angle in Degrees	Sin of Angle
1 in 30	1·91	·0333
1 in 25	2·29	·04
1 in 20	2·87	·05
1 in 18	3·18	·0555
1 in 16	3·58	·0625
1 in 14	4·09	·0714
1 in 12	4·78	·0833
1 in 10	5·73	·1
1 in 9	6·38	·1111
1 in 8	7·18	·125
1 in 7	8·22	·143
1 in 6	9·6	·1667
1 in 5	11·53	·2
1 in 4	14·48	·25
1 in 3	19·45	·3333

Power required to Drive an Inclined Plane

If we wish to obtain a simple equation, showing the energy required to propel an aeroplane, we can proceed in the following manner :—

$$P\alpha = \frac{\alpha P_{90}}{30}$$

$$\text{and } P_{90} = \cdot 003AV^2$$

Where A is the area of the plane in sq. feet, and V the velocity in miles per hour :—

$$\therefore P\alpha = \frac{\alpha \times \cdot 003AV^2}{30}$$

$$\therefore \text{the drift, or the resistance} = P\alpha \sin \alpha$$

$$= \frac{\alpha \times \cdot 003AV^2 \sin \alpha}{30}$$

In addition to the resistance of the plane, there will be a head resistance due to the body, struts, etc. If the *equivalent* area of these, in square feet, equals S, then the head resistance will $= \cdot 003SV^2$.

$$\therefore \text{the total resistance or drift D will} = (\cdot 003\,S + \alpha \sin \alpha \times \cdot 0001\,A)\,V^2$$

$$\therefore \text{the horse-power will} = \frac{88\,(\cdot 003\,S + \alpha \sin \alpha \times \cdot 0001\,A)\,V^3}{33000}$$

Thus, the power varies as the cube of the speed, if the angle is kept constant.

As the speed increases it will be necessary, if the lift is to be kept constant, to decrease the inclination of the plane, and this will effect a corresponding reduction in the drift.

Aspect

If an inclined plane is driven forwards, it will impress a downward velocity on a certain volume of air.

The amount of air so depressed will depend upon the size and "aspect" of the plane, and also upon its inclination.

The aspect of a plane is the ratio $\frac{\text{length}}{\text{width}}$. If the width

is at right angles to the direction of motion, the plane is in "width aspect." If the length is at right angles to the direction of motion, the plane is in "length aspect." The amount of the lift of the aeroplane will depend upon the amount of the downward momentum given to the air

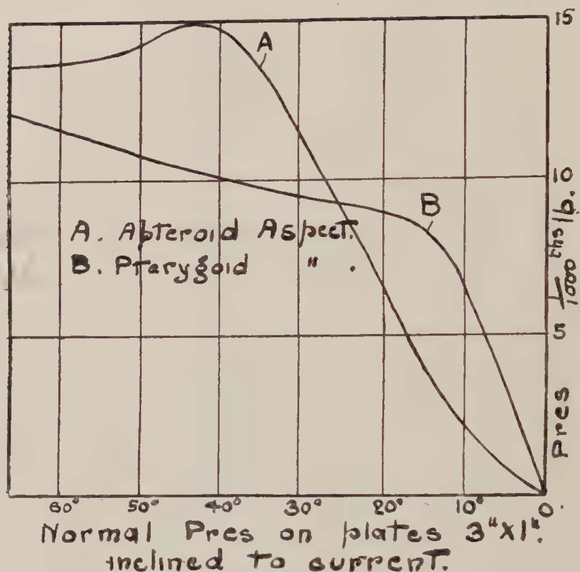


FIG. 4.—Curves for inclined planes in length and width aspect. (Stanton.)

$=MV$, where M is the mass of air engaged and V is the velocity given it.

Now, the energy given to the air, that is kinetic energy or energy *lost*, $=\frac{1}{2}MV^2$.

Suppose we have a given weight to support; then, the downward momentum to be given to the air in every unit of time is known, and equals MV. We can make M as small as we like in this expression, providing we make V sufficiently large.

If we halve the mass acted upon, then—

$$MV = \frac{M}{2} \times V^1 \therefore V^1 = 2V.$$

Consequently—

$$\frac{\text{Energy lost in second case}}{\text{Energy lost in first case}} = \frac{\frac{1}{2}M \times (2V)^2}{MV^2} = \frac{2}{1}$$

i.e., by halving the mass of air acted upon, the power required to support the plane is doubled.

Hence, it is clearly advantageous *to engage as much air as possible.*

This can be done—

(1) By increasing the spread of the aeroplane, or by mounting one plane upon another, thus increasing the amount of entering edge.

(2) By increasing the speed.

In Fig. 4, the curve A shows the lift of an inclined plane 3″ × 1″ in "width aspect," and the curve B, the same plane in "length aspect." These curves were taken by Dr Stanton.* It will be seen that the lift of the plane between the angle of 0° and 10° in "length aspect," is much greater than in "width aspect."

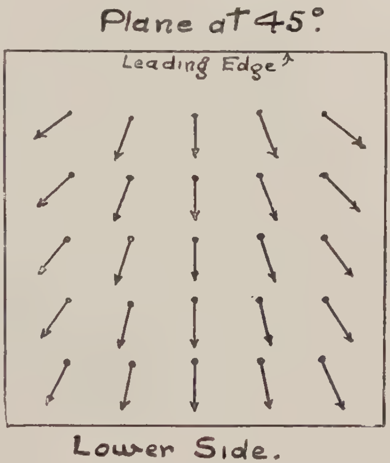


Fig. 5.—The direction and flow of air about a plane.

The superior lift of the plane in "length aspect" is almost wholly due to the fact that, in this position, it is able to engage more air than when in "width aspect"; also, when the plane is in "length aspect," there is less escape of air at the sides, and this also adds to its superiority.

To test this, Mr Dines, F.R.S., placed a plane, which was provided with a number of pins carrying short ribbons, in a current of air, and took a snapshot of it.

Fig. 5 shows the direction in which the ribbons set themselves. The inclination of the side ribbons proves that the air escaped at the sides of the plane.

* *Proceedings of the Institution of Civil Engineers*, vol. 156.

Fig. 6 is a stream-line photograph of the underside of an inclined rectangular plane. The column of air is marked by jets of smoke. It will be seen that the outer jets curve round and flow over the sides, the greatest deflection taking place at the front edge.

The loss by side leakage may be reduced by decreasing the proportional length of the sides, *i.e.*, by increasing the "length aspect."

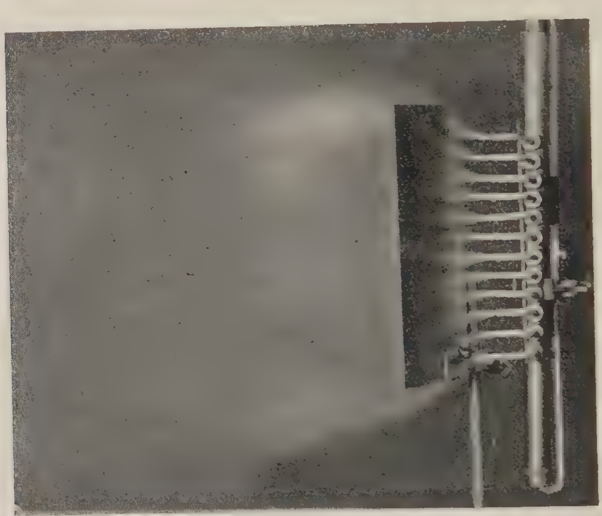


FIG. 6.—Stream-line flow about an inclined plane.

LANGLEY'S LAW

Suppose we have a plane which is to lift a given weight; (1st) at velocity v, and (2nd) at velocity $2v$.

In the first case—If $M =$ mass of air engaged, the weight supported will be $\propto$ to Mv, and work lost will be $\propto$ to Mv^2.

In the second case—Since the velocity is doubled, twice as much air will be engaged. Hence, it will only be necessary to set the plane at such an angle that the air will be forced down with velocity $\frac{1}{2}v$.

The weight supported will be $\propto$ to $2M\frac{v}{2} = Mv$, and work lost will be $\propto$ to $2M\left(\frac{v}{2}\right)^2 = \frac{1}{2}Mv^2$.

$$\therefore \frac{\text{Work lost in first case}}{\text{Work lost in second case}} = \frac{2}{1}$$

i.e., by doubling the speed, we have halved the work done. Consequently, "*the power to drive an aeroplane varies inversely as the speed.*" This is Langley's law. It does not hold in practice, because an aeroplane always has a certain amount of "head resistance," which varies directly as the square of the speed. Langley's law applies to the "supporting momentum," and not to the head resistance. Although the power required to drive an aeroplane is not so favourable as Langley's law would appear to show, it has been clearly demonstrated that it does not increase at the same rate as for other means of locomotion, which appear to vary directly as the cube of the velocity.

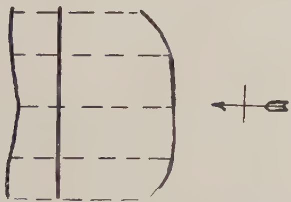


Fig. 7.—Pressures on the back and front of a narrow plane. (Stanton.)

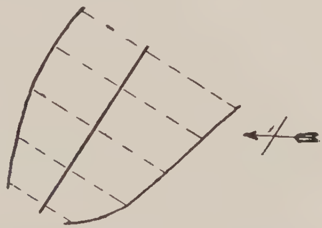


Fig. 8.—Pressures on the back and front of an inclined plane at 60°. (Stanton.)

The Distribution of Pressure on Normal and Inclined Planes

The variation of the distribution of the pressure with change of inclination, has been well shown by the following diagrams by Dr Stanton.

In Fig. 7, with the plane normal to the wind, the right-hand curve shows the compression and the left-hand curve the suction, on the front and back of the plane respectively. The ratio of the maximum pressure or the windward side to the suction on the leeward side of a circular plate was found to be 2·1 to 1, whereas the ratio for a rectangular plate (aspect ratio 25 to 1) was 1·5 to 1.

Fig. 8 shows the same plane inclined at 60° to the current. The greatest compression and suction are now toward the leading edge.

As the inclination is still further decreased to 45 (Fig. 9), the difference between the pressures at the leading and trailing edge is still greater.

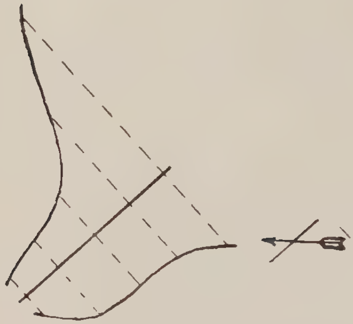


FIG. 9.—Pressures on the back and front of an inclined plane at 45°. (Stanton.)

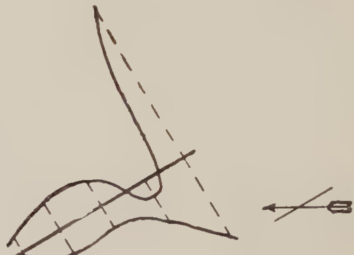


FIG. 10.—Pressures on the back and front of an inclined plane at 30°. (Stanton.)

When the plane is set at 30°, as in Fig. 10, the air receives a jerk when it meets the front edge of the plane. This produces a great suction at first, but afterwards the

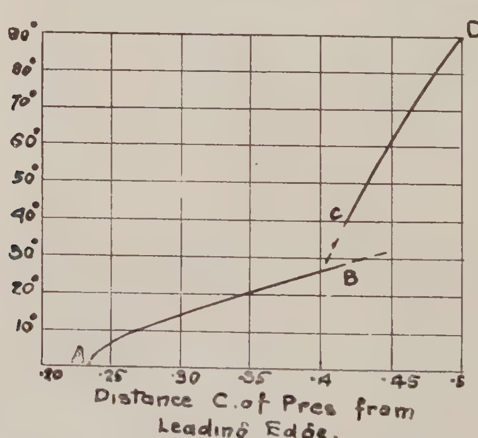


FIG. 11.—The centre of pressure for various inclinations of a flat plane. (Rateau.)

air springs back and causes a compression on the back of the plane. It then rebounds again, causing a second suction.

It will further be noticed from these diagrams, that

the suction from front to back varies at a greater rate with decrease of inclination, than does the compression.

The variation of the distribution of the compression and suction has the effect of causing the centre of pressure, *i.e.*, the point of action of the resultant force, to travel towards the front edge as the inclination is decreased. This was first noted by Sir George Cayley in 1809.

In Fig. 11 is shown Prof. Rateau's diagram for a flat plane. The inclination of the plane to the wind is marked

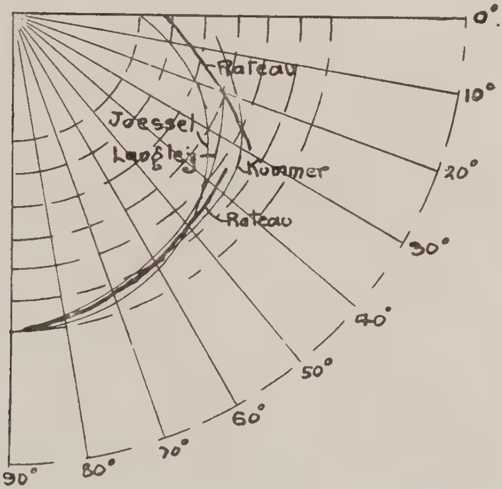


FIG. 12.—The centre of pressure for various inclinations of pressure on circular diagram (Rateau, Wessel, Langley, Kummer).

off along the vertical, and the distance of the centre of pressure from the leading edge, in terms of the width, is marked off along the horizontal.

Between angles of 30° and 40° the curve is discontinuous.

Prof. Rateau's results agree very closely with a formula obtained by Joessel in 1870 for water, and verified later by Avanzini for air.

Joessel and Avanzini $\triangle = \cdot 3\,(1 - \sin \alpha)\,L$.

Where $\triangle$ = distance from the centre of area to the centre of pressure, L = width, α = inclination in degrees.

Fig. 12 shows plotted on a circular diagram the results of various investigators on the centre of pressure.

The travel of the centre of pressure also varies with the plan-shape of a plane. Thus, in Fig. 13 we see the locus of the centre of pressure for a rectangular, semicircular and circular plane. Curves 1 and 2 show the travel of the centre of pressure for the rectangular plane in length and width aspect respectively. The aspect ratio

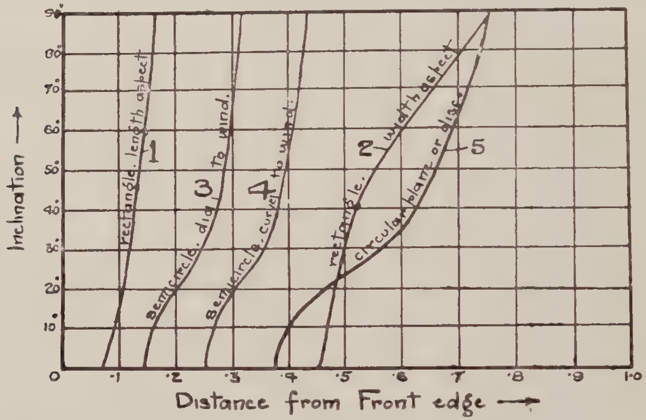


FIG. 13.—The centre of pressure for various inclinations of a rectangular, semicircular and circular plane.

of the plane was 4·5 is to 1, and the distance from the front edge is set out along the base line in terms of the length of the rectangle. Curves 3 and 4 relate to the semicircular plane with the diameter and the curve to the wind respectively. The distance of the centre of pressure from the front edge is set out along the base line in terms of the diameter, which corresponds with the length of the rectangular plane. Curve 5 is the centre of pressure curve for the circular plane.

CHAPTER II

Aerocurves

The wings of all birds are curved. Therefore it would appear that this shape must possess some great virtue not possessed by a plane surface.

It was left for Mr Phillips to make this discovery, and to patent his invention in 1884. Every flying machine now uses this invention.

If a diagram of the pressure on the back and front of an aerocurve is taken, corresponding to Fig. 10, it will be found that there is a particular angle at which the pressures on the front edge are very small.

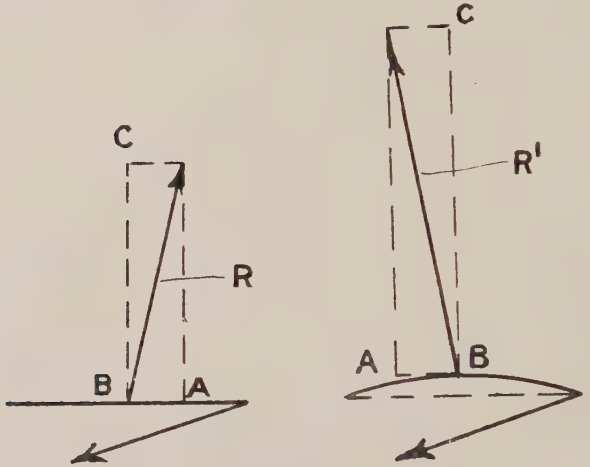
There is no *shock entry* upon the air, as is shown in Fig. 10. The superiority of the aerocurve is due to the fact that it is able to meet the air with a *minimum of shock*, and to curve it round afterwards with a continuously increasing velocity, until it is discharged at the trailing edge, thus obviating a "surface of discontinuity." Further, contrary to general belief, Sir Hiram Maxim has found that, for minimum resistance, an aerocurve should be as thin as possible, consistent with strength.

Otto Lilienthal, a Danish engineer, was one of the first to appreciate the virtues of aerocurves, and the following explanation of their superiority over a plane surface is due to him.

Suppose we have a flat and a curved aeroplane gliding down in the direction of the arrow, as shown in Figs. 14 and 15. In the case of the flat plane, the resultant R may be resolved into components BA and BC, parallel and normal to the plane. The parallel, or "tangential" BA, always opposes motion. Lilienthal found that with the curved plane (Fig. 15), the tangential component AB of the resultant R^1 acted *in the direction of motion* for angles between 3° and 30°. The maximum effect took place at 15°, and then the component AB equalled $\frac{1}{12}$th the normal component or lift BC.

The Wright Brothers and other experimenters, have verified the existence of the "tangential," although they obtained different values for the constants.

The angle α (Fig. 16) is known as the angle of incidence,



FIGS. 14 and 15.—Lilienthal's explanation of the superior lifting effect of a curved plane.

of attack, or of inclination; the angle B as the angle of entry, and the angle γ as the trailing angle. A satisfactory formula connecting lift with α, B and γ, does not appear to have been obtained yet. It may be taken that a well-made aeroplane, at an angle of 7°, or 1 in 8, will lift 2·75 lbs. per sq. ft. at a velocity of 40 miles per hour.

Fig. 17 shows a curve (Maxim) giving the lift and drift

FIG. 16.—The aerocurve. Angle of attack and entry, trailing angle.

in lbs. per sq. ft. for an aeroplane shaped as shown in Fig. 18.

In view of the fact that the curves of pressure distribution for aerocurves are different from those for aero-

planes, we should expect the travel of the centre of pressure to be different.

It is found with an aerocurve that the centre of

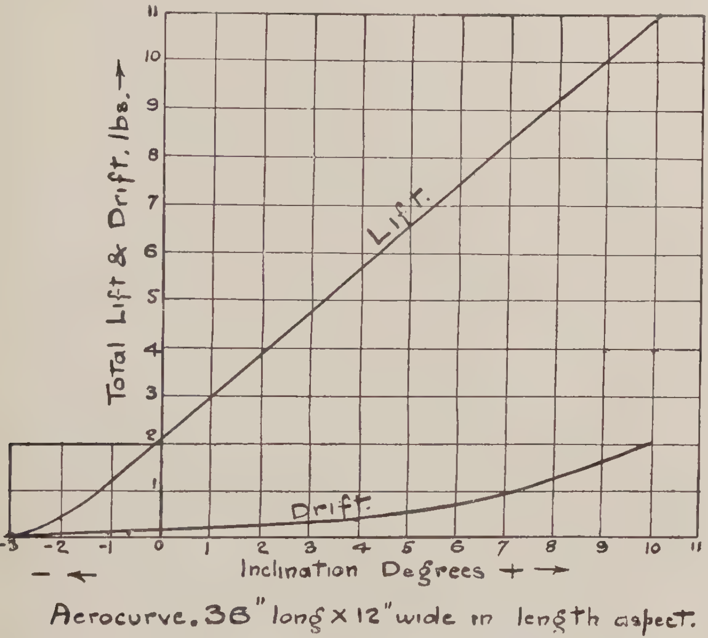


FIG. 17.—The aerocurve. Curve showing the lift and drift. (Maxim.)

pressure travels up towards the front edge with decrease of inclination, until a certain critical angle is reached, after which the centre of pressure travels backward with a further decrease of inclination.

In Fig. 19 is plotted the locus of the centre of pressure of an aerocurve, having a aspect ratio of $1\frac{1}{2}$ and a curvature

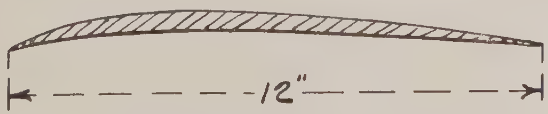


FIG. 18.—Aerocurve used in Fig. 17.

of $\frac{1}{12}$th the span. Curve 1 was obtained when the hollow was downwards and curve 2 when the hollow was upwards. In curve 1 the reversal of the centre of pressure is clearly

shown, while in curve 2 it is seen that the centre of pressure advances continually until it is at last in front of the

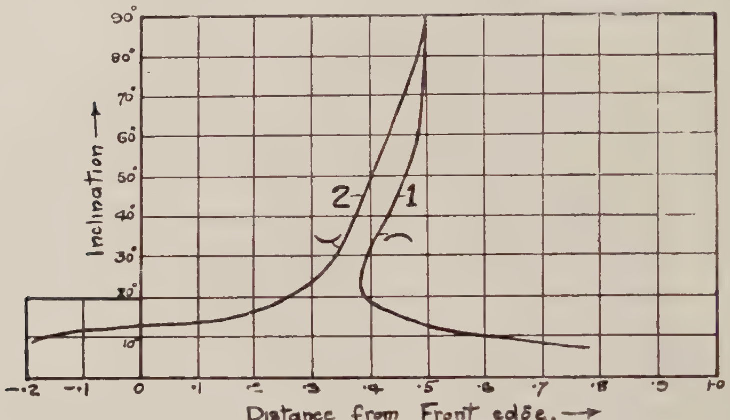


FIG. 19.—Centre of pressure curve for an aerocurve with the hollows downwards and upwards.

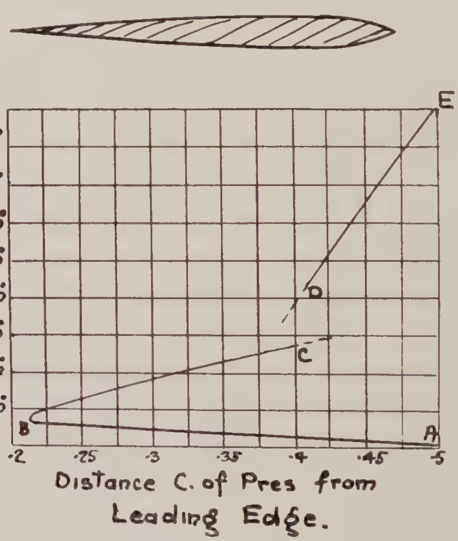


FIG. 20.—Centre of pressure for ship-shaped sections and aerocurves.

leading edge of the plane. This great advance is largely due to the effect of the head resistance.

Fig. 20 shows a curve obtained by Prof. Rateau for a ship-

shaped section, which is very similar to the curve obtained for a certain shape of aerocurve.

The travel of the centre of pressure, of course, varies

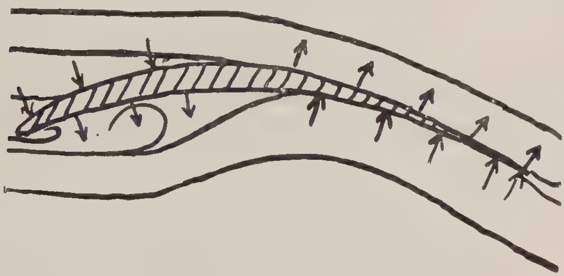


FIG. 21.—The flow of air about an aerocurve.

with the shape of the aerocurve, and until the matter is thoroughly investigated in the laboratory, it is useless to attempt to give a formula connecting the travel with curvature and inclination.

The reversal of travel of the centre of pressure greatly affects the design of flying machines, because it makes it impossible to obtain automatic stability with an arc-shaped aerocurve placed with the hollow downwards. This reversal is due to the fact that at small angles the wind strikes the upper side instead of the lower side of the aerocurve, as shown in Fig. 21, and thus, the front portion

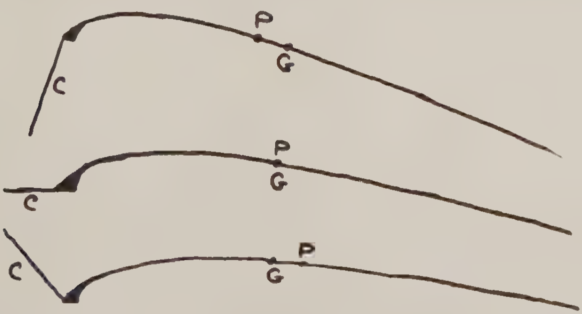


FIG. 22.—The centre of pressure on aerocurves. (Wrights.)

which is the most effective part in the case of a flat plane, altogether ceases to lift.

The Wright Brothers, in one of their early gliders

(1901), having given the plane a curvature of $\frac{1}{12}$, found that the machine was very difficult to control. They were in doubt as to the reason for this until, when flying the machine as a kite, they noticed that in light winds it flew as shown in the upper figure (Fig. 22), but that, as the wind became stronger and the angle of incidence less, the machine flew as shown in the middle figure, with a slight horizontal pull. When the wind became much stronger, it took the position shown in the lower figure, with a strong downward pull.

Thus, it was evident that, in the first case, the centre of pressure was in front of the centre of gravity; in the second the centres coincided; while in the third, the centre of pressure was behind the centre of gravity. The curvature was then reduced, and complete success obtained.

Stream Lines

The explanation of the superior lift of an aerocurve over an aeroplane, is due to the fact, as we have seen, that it is a stream line surface.

A stream line is the locus of the successive positions of a particle of moving fluid, and it must always be a continuous curve, since it is impossible to make a fluid instantly change its direction of flow. If the body is so shaped that it has sharp corners or recesses, the fluid flows past these, leaving pockets, and forming what are known as *surfaces of discontinuity*.

Now, the total energy of a pound of fluid = Potential energy + Pressure energy + Kinetic energy

$$= h + \frac{p}{w} + \frac{V^2}{2g}$$

$\therefore$ whenever we have a change in the velocity of a fluid, it follows that this can only be derived at the expense of the pressure, or the potential energy.

The pressure and the potential energy are generally not very great (in the cases we are considering, the potential energy cannot be utilised, and may therefore be neglected), and, therefore, the force available for changing the direction of flow is not great.

Therefore, since force = mass times acceleration, the change of the direction of flow cannot be made great. Hence, the reason for the formation of surfaces of discontinuity.

Fig. 23 is a diagram illustrating the formation of surfaces of discontinuity about a rectangular bar.

The air flows in the direction of the arrow until it meets the bar. It then divides on the front edge. As the air is unable to turn sharply round the front corners, it forms a surface of discontinuity, producing a rarefaction at these places. The air then flows along the sides until the rear corners are reached, when again a surface of discontinuity is formed, producing a rarefaction on the back.

The effect of a surface of discontinuity upon the pressure diagram is well shown in Fig. 10.

Figs. 24, 25, 26 and 27 show stream line photographs, taken, with the assistance of Mr A. G. Field, at East

FIG. 23.—Stream lines about a rectangular bar.

London College, of the flow of air about variously-shaped bars.

Fig. 24 shows a rectangle "broadside on."

The air divides at the middle of the front edge, and forms a surface of discontinuity, with consequent rarefaction on the back edge.

In Fig. 25 is shown the same rectangle inclined.

The circular section shown in Fig. 26 causes less disturbance to the air than the previous sections, and therefore offers less resistance to motion. Again, there is a surface of discontinuity at the back, but this is not so hard and well-defined as in the previous case.

Fig. 27 shows the flow of air about a triangular bar with the front edge to the wind. There is a well-defined surface of discontinuity at the back.

Fig. 28 illustrates the flow of lines of smoke about an aerocurve inclined at a small angle.

The air divides at the front edge and hugs both sides as it passes along; its resistance to change of motion causing a compression on the lower side of the plane and

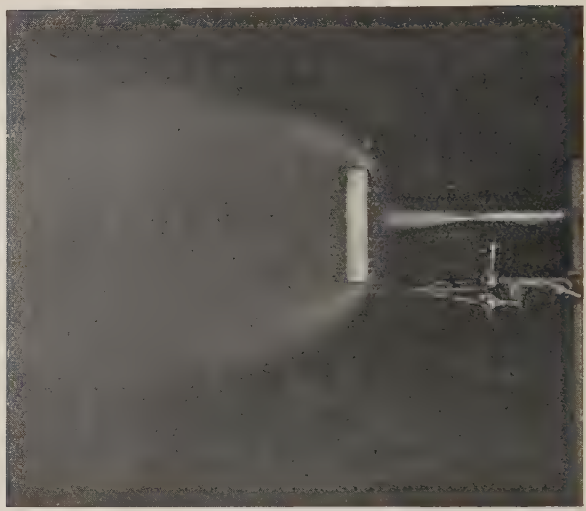


FIG. 24.—Stream line flow about a rectangular bar, broadside on.

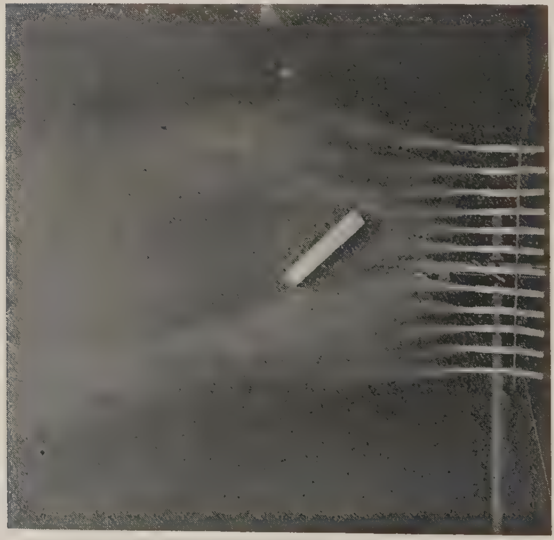


FIG. 25.—Stream line flow about an inclined rectangular bar.

a rarefaction or suction on the upper side. As the inclination is increased, a critical angle appears to be reached,

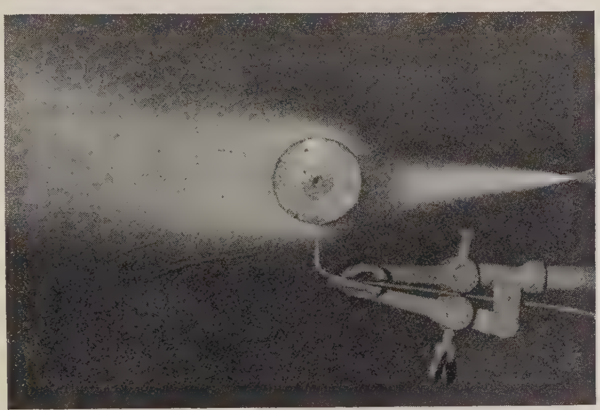


FIG. 26.—Stream line flow about a circular bar.

FIG. 27.—Stream line flow about a triangular bar.

after which the stream line ceases to follow the upper side and forms a surface of discontinuity with corresponding

eddies (Fig. 29). Also the current divides at a point below the front edge, as shown in Fig 30, which was taken in

Fig. 28.—Stream line flow about an aerocurve at a small inclination.

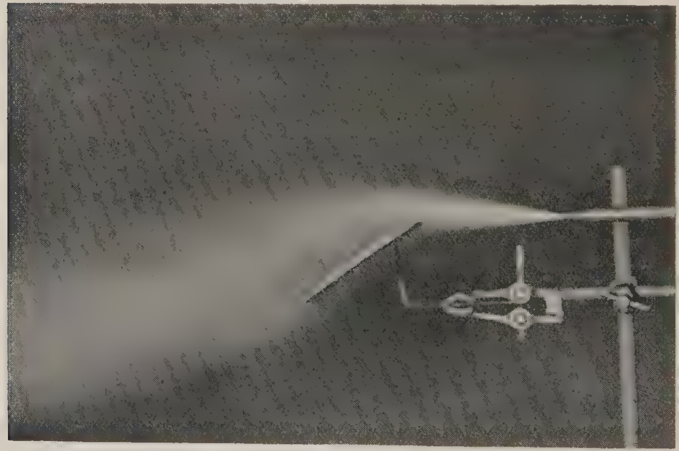


Fig. 29.—Stream line flow about an aerocurve at a large inclination.

water by Prof. Hele Shaw. It will follow that there must be an inclination at which these two forms of flow merge

into one another. According to some experiments made by Prof. Rateau, it would appear that, at the time the one system of flow is merging into the other, there is in-

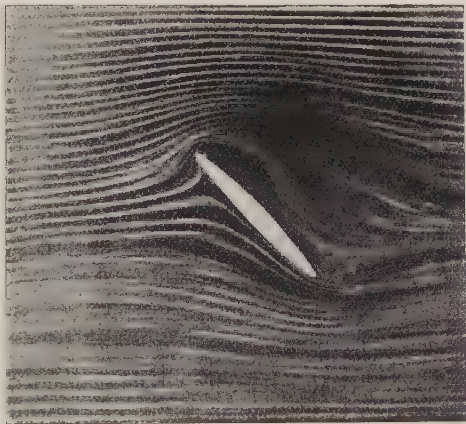


FIG. 30.—Stream line flow (water) about an aerocurve.

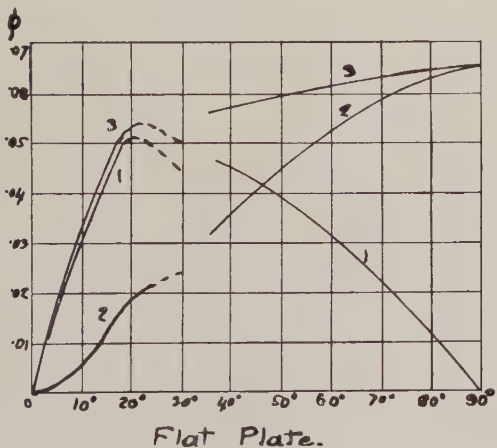


FIG. 31.—Pressure curves for inclined planes. (Rateau.)

stability. Thus, in Figs. 31 and 32, each curve is in two distinct and disconnected portions. The hump in Mr Dines' curves for square and other inclined plates is probably due to the same cause.

The flow of air under a plane is shown in Fig. 33, it being noticed that there is a slight tendency to rise at the front edge with this large angle.

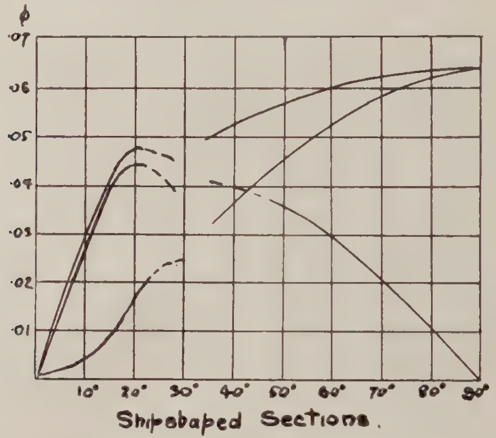


FIG. 32.—Pressure curves or inclined planes, ship-shaped sections. (Rateau)

FIG. 33.—Stream line flow beneath plane

The air affected by an aeroplane, that is the field of an aeroplane, is greater than the air lying in its path. Thus, in Fig. 34, it will be seen that air, which is considerably

above the front edge of the plane, is within the range of the plane and is deflected downwards. The flow and

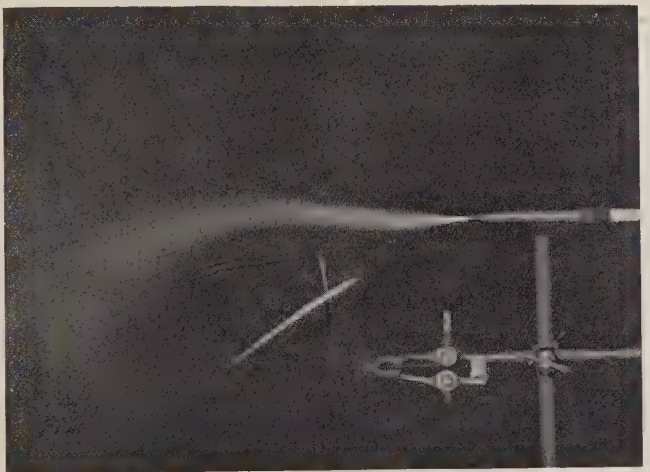


FIG. 34.—Stream line flow above plane.

FIG. 35.—Stream line flow between biplanes.

dispersion between the planes cf a biplane are shown in Fig. 35.

Stream Line Surfaces

A stream line surface is one which does not cause a surface of discontinuity to be formed.

A fish is one of Nature's stream line surfaces. The greatest section is in front of the mid-section and the tail portion has much finer lines than the head portion.

When a body, shaped as shown in Fig. 36, is subjected to a moving current, it is found that the pressure on the body at every point is as shown by the direction of the

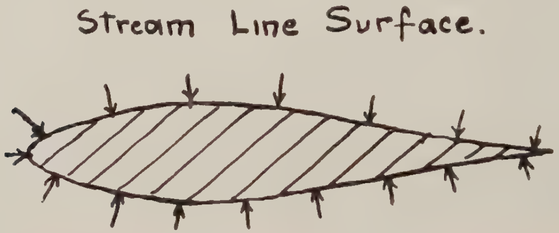


Fig. 36.

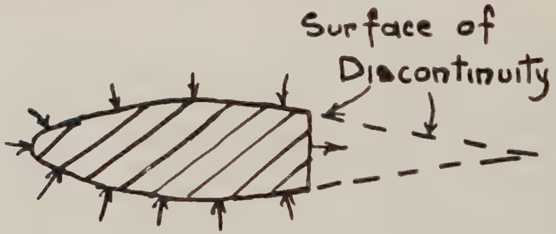


Fig. 37. Figs. 36 and 37.—Stream line surfaces.

arrows. If the resultant of all these forces is taken, it will be found to be small and to oppose the direction of motion.

Now, if the back portion is cut away, as shown in Fig. 37, a surface of discontinuity or rarefaction is formed at the back, and the resultant of all the forces is much greater. That is, the force required to drive a body so shaped is much greater than in the case of a stream line body.

Hence it is evident that, in a flying machine, every surface should be, if possible, a stream line surface, in order to avoid loss of energy due to surfaces of discontinuity.

The surface which has been found to require the minimum power to drive is a long fish-like surface with the blunt end towards the direction of motion. It was found

that when the same body was placed with the thin end opposed to the wind that the driving force was greatly increased.

Resistance of Bodies

When we come to consider the resistances of variously shaped bodies to motion, we find that there is a great lack of available data.

We may take it as being well-established that, with most bodies, the resistance varies as the square of the velocity.

The resistance for a normal plane, according to the Eiffel Tower formula $= \cdot 003\ A\ V^2$—

$A =$ area in square feet,
$V =$ velocity in miles per hour.

The following formulæ for bars of various sections have been deduced from experimental data obtained by Sir Hiram Maxim nearly twenty years ago.

It is not contended that these are exact values, but in our present state of knowledge they are the best available; and, although they will probably be considerably modified, they should be found useful in the design of machines.

Square bar, with face normal to wind—
$P = \cdot 0039\ A\ V^2$, where
$A =$ area in square feet of one face
$V =$ velocity miles per hour.
Modulus $K =$ (in the expression $P = K\ (\cdot 003\ A\ V^2)$) $= 1 \cdot 3$.

Square bar, with one diagonal in line with the wind—
$P = \cdot 0041\ A\ V^2$,
$A =$ area square feet of one face.
Modulus $= 1 \cdot 365$.

Round bar—
$P = \cdot 0022\ A\ V^2$,
$A =$ area of cross-section through a diameter.
Modulus $= \cdot 733$.

Ellipse-major diameter $=$ twice minor diameter—
$P = \cdot 0013\ A\ V^2$,
$A =$ area of cross-section through the minor diameter.
Modulus $= \cdot 43$.

Pointed body. Length $= 6$ times thickness—
$P = \cdot 00016\ A\ V^2$, where
$A =$ area of section through A B in square feet.
Modulus $= \cdot 0533$.

Fish-shaped body—
Thick end to wind—
$P = \cdot 000195\ A\ V^2$.
Modulus $= \cdot 065$.

Thin edge to wind—
$P = \cdot 0005\ A\ V^2$.
Modulus $= \cdot 167$.

The above formulæ may be taken to apply to bodies in which the smaller dimension varies from $\frac{1}{4}''$ to $6''$.

If the body is a long one, and the dimensions small, the resistance appears to be out of proportion to the size. This is particularly to be noticed in the case of bracing wires, and is probably due to the fact that the body oscillates sideways, and so collides with more air than it would otherwise do. Therefore, in calculating the re-

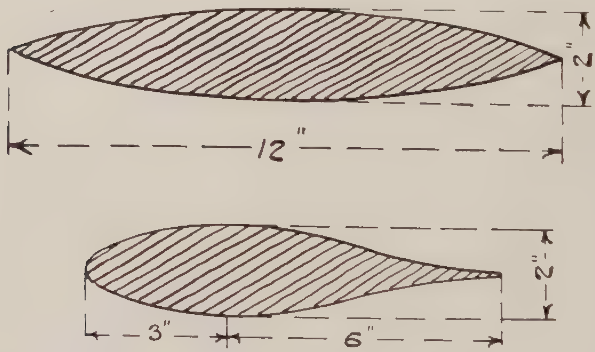


FIG. 38.—Sections of bars. (Maxim.)

sistance of wires, an ample additional allowance should be made to meet this extra resistance.

In constructing a machine, special precautions should be taken to minimise this oscillation by connecting the wires together where they cross.

SHIELDING

An interesting point in calculating the resistance of a machine is the shielding effect one body has on another following in its wake.

This question has been partly explored by Dr Stanton. He mounted two discs of equal size on the same spindle, and arranged that the distance between them could be varied. It was found (Fig. 39) that, when the two discs

were close together, the total pressure was only very slightly greater than that of a single disc. As the discs were separated, the pressure decreased until a minimum was reached at a distance apart of 1½ diameters, being then less than 75 per cent. of the resistance of a single plane.

As the discs were moved still further apart, the pressure increased.

At a distance of 2·15 diameters, the pressure was again equal to that on a single disc.

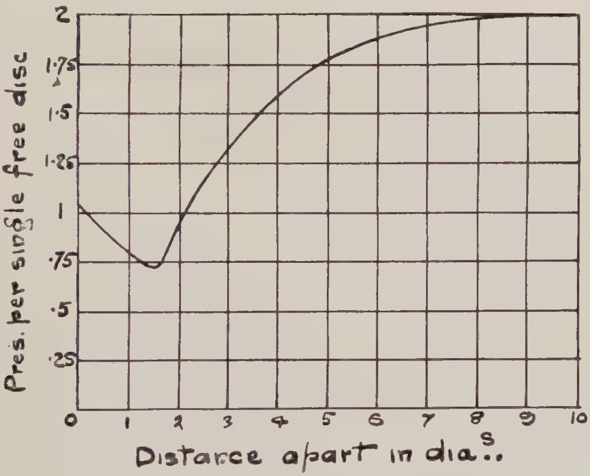


FIG. 39.—Shielding of circular plates. (Stanton.)

At a distance of 5 diameters, the total pressure was 1·78 times that on a single plate.

It will be seen from the curve that the total pressure is not double that on a single plate until the plates are separated by a distance equal to 10 diameters.

Therefore, in calculating the resistance of struts placed one behind another, it may be assumed safely that no shielding takes place if they are at a distance apart equal to 10 times the smallest dimension.

CHAPTER III

Automatic Longitudinal Stability and Manual and Automatic Control

The greatest obstacle to the solution of the problem of flight has been the problem of stability and control.

Fig. 40.—Path of gliders, having various centres of gravity.

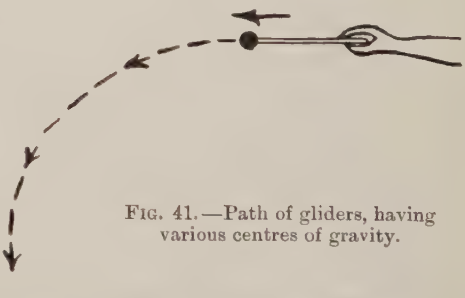


Fig. 41.—Path of gliders, having various centres of gravity.

Its solution was achieved in a graduated and upward path by Lilienthal, Pilcher, Chanute, and the Wright Brothers.

If we take a flat plane in which the centres of area and of gravity coincide, and launch it into the air, it rolls over and over thus (Fig. 40).

If we weight it at the front, so that the centre of gravity is not more than one-fifth of the width from the front, then it takes a header downwards, thus (Fig. 41).

If we then gradually reduce the weight, we shall at last arrive at a point at which the plane will glide in a perfectly straight line A B (Fig. 42).

When this is so, we shall find that the centre of gravity is between ·25 and ·3 of the width from the front edge.

In the first case, the centre of pressure is ahead of the centre of gravity, and introduces a couple, which rotates the plane.

In the second case, the centre of gravity is so far ahead that it drags the plane into the vertical at once.

In the third case, the centres of pressure and of gravity coincide when the plane is at the natural inclination, with the result that the plane glides in a straight line.

By utilising the variation of the centre of pressure with the inclination of the plane, it is possible to make a glider automatically stable.

A glider can be made to perform two kinds of oscillations,—

(1) It can be made to flutter, or oscillate, about an axis at right angles to the line of flight; or

(2) It can be made to "loop the loop," or follow any one of a number of curved paths.

FIG. 42.—Path of gliders, having various centres of gravity.

1. In the first case, when the glider is travelling at the natural velocity, and at the correct angle, the centre of pressure and of gravity coincide; but if the angle is too small, the centre of pressure advances and introduces a couple, which tends to restore the glider to the correct angle. Now the glider has a certain inertia, and thus, when the correct angle is reached and no couple is acting, it continues to rotate to a greater angle. As soon as the natural angle is exceeded, the centre of lift travels behind the centre of gravity and introduces another couple, tending to reduce the inclination. This sets up a short, or quick, oscillation.

This oscillation is damped out by the resistance offered by the air to an oscillating plane.

We have thus explained the reason for the short-pitched oscillation, and we have established one of the necessary

conditions of equilibrium, namely, that for *automatic longitudinal equilibrium* it is necessary that *the centre of gravity must be within the path of travel of the centre of lift.*

2. If the angle of the glider is the correct one for horizontal flight at the natural velocity, and the speed is too high, then the lift becomes too great, and this produces an added vertical velocity C B. Thus, the line of travel of the machine is along the line A C.

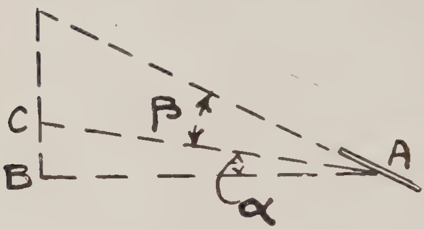


FIG. 43.—Path of gliders, having various speeds.

Now the effect of this, as will be seen from Fig. 43, is to decrease the inclination of the plane relatively to the line of flight from the angle $\alpha+\beta$ to β. The centre of pressure will therefore travel forwards, and introduce a couple which tends to increase the inclination.

As a result of this added inclination, the inclination of the path of travel will be still further increased, and if the original speed be sufficiently great, the glider would "loop the loop."

If the launching speed of the glider is not sufficient, it will fall until the weight and lift are equal, and opposite. Thus, instead of travelling from A to B, it will travel down the path A C. The angle of inclination, relatively to the line of flight, will therefore be $=\alpha+\beta$. As a result of this increase of relative inclination, the centre of lift will travel backwards and will introduce a couple, tending to decrease the inclination of the glider. This will cause the glider to fall until the velocity is sufficient to right it.

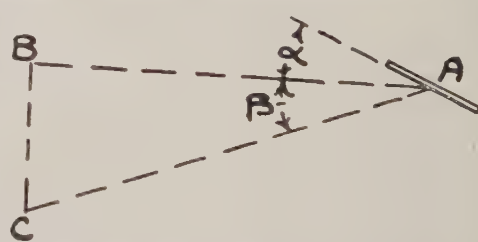


FIG. 44.—Path of gliders, having various speeds.

Supplementary or Rider Planes

The longitudinal stability may be made more rigid by the introduction of a second plane set at a distance from the main plane.

The amount or rigidity of the equilibrium depends in part upon the distance between the two planes.

In the Wrights' machine, there is a small plane placed horizontally in the front, which, under normal conditions, rides parallel with the wind.

If the inclination of the plane becomes too small, the path being along the line D C, the front plane A will be set at a negative angle to the wind, and thus the reaction will act downwards.

With decrease of inclination, the centre of lift travels

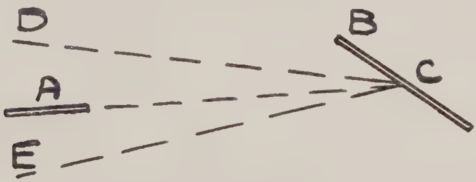


Fig. 45.—The effect of disposition of the planes on the Wright machine.

forwards, and introduces a couple tending to increase the angle of inclination.

The effect of the rider plane A is, therefore, to limit or reduce the travel of the centre of lift forwards.

If the inclination of the machine becomes too great, the rider plane will also commence to lift.

With increase of inclination, the centre of lift travels backwards. The backward travel will, therefore, be limited or reduced by the rider plane.

Thus the effect is, that the travel of the centre of lift and, therefore, the couple resisting displacement, is *reduced* by setting the rider plane at a *negative angle*. A large displacement is therefore required to give a comparatively small restoring couple.

Thus the Wright machine is bound to oscillate through large angles.

Means are provided for flexing the elevating plane in either direction to control the machine. Nevertheless, the fact remains that the Wright disposition of the planes

gives just the *opposite effect* to that which is required for stability, the principle of stability being, that *for maximum stability the travel of the centre of lift to either side of the centre of gravity must be a maximum for a given increase or decrease of the angle of inclination.*

It follows, from a similar reasoning, that the *stability may be increased by setting* the front plane at a *greater or positive angle* with the back plane.

It now remains to consider the methods of increasing the travel of the centre of lift, and of damping out any oscillation which may be set up by a change of inclination.

If we place a second plane of a certain aspect and area, either before or behind the main plane, and parallel to it, the line of flight becomes more nearly straight.

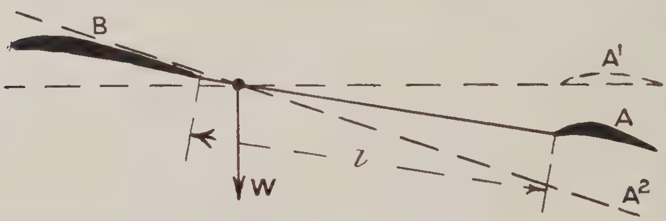


FIG. 46.—Diagram illustrating the effects of rider planes on the automatic stability.

(1st Case.) *Small plane behind.*

A *small plane*, A, *behind* the main plane B.

With such a disposition, the centre of gravity will be near the main plane.

Now, behind the main plane, there is a certain wash, or wake, of disturbed air, the lifting properties of which are not so good as those of undisturbed air.

Thus, as the tail plane rises to A^1, the diminution of the lift is greater than it would be in a clear run of air.

For the same reason, as the tail falls to A^2, the lift increases at a greater rate than it would do in free air.

This is equivalent to *increasing the range of travel* of the centre of lift—*i.e.*, of increasing the restoring couple.

It follows that the amount of this additional restoring couple varies as the length l between the planes.

Damping

If there were no damping, and the machine received a displacement, it would go on oscillating for ever about the neutral line of inclination.

The speed with which an oscillation dies out depends upon the damping effect of the planes. Now, the resistance of a normal plane is proportional to the square of the velocity. If the machine is to oscillate about the point X, then the velocity v^1 of the plane B, to that of v^{11} of A, is as a is to b.

Let A = area of plane A, and B = that of plane B.
Then $A \times b = B \times a =$ constant,
$\therefore$ Damping effect $\propto$

$$A\,(v^{11})^2\,b \propto A\,b^3$$
$$\propto (A\,b)\,b^2 \propto b^2,$$

i.e., the damping couple for the tail increases as the square

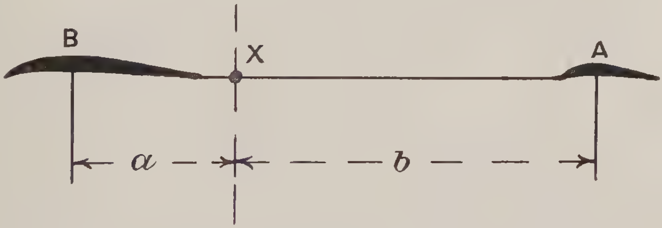


Fig. 47.—Diagram illustrating the effects of rider planes on the automatic stability.

of b, or, in other words, the greater the distance between the planes, the greater the damping effect.

(2nd Case). Small plane in front.

There is less shielding of the back plane when the small plane rises to the position A^1. Therefore, as before, the lift of the plane B will vary at a greater rate than if the plane were acting in free air.

This will be equivalent to an increase in the travel of the centre of lift and the restoring couple.

We may increase the sensitiveness by arranging that the lift of A shall decrease at a less rate than that of B.

This can be done by giving the front plane A a greater aspect ratio than the plane B, because the normal pressure

on a normal plane is practically independent of the aspect; but, as the inclination is reduced, the normal pressure per unit area is greatest on the plane having the greatest aspect ratio. Therefore, the greater the aspect ratio of the plane A, the greater the restoring couple. This couple may be still further increased by *extending the front plane*, so that the *maximum interference* with the back plane may be obtained.

The opposite reasoning must be applied when the plane is at the rear, as in that case it is necessary with decrease of inclination to decrease the pressure on the tail at a greater rate than on the main plane.

The shape having the maximum variation of lift with

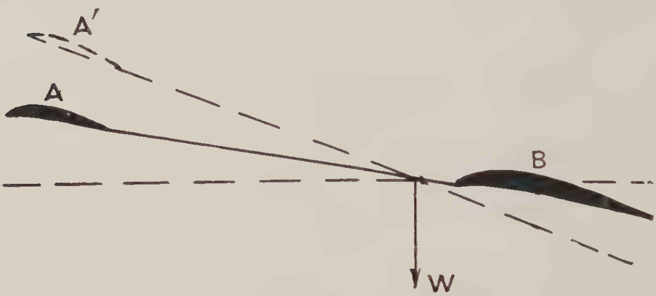


FIG. 48.—Diagram illustrating the effects of rider planes at the automatic stability.

inclination appears to be a triangle with the apex facing the wind.

Therefore, we see that for *maximum stability*,—

(1) If the *small plane* is *in front*, it should have a *large aspect ratio* and a *long span*.

(2) If behind, it should have a *comparatively small aspect ratio* and preferably be *triangular* with the *apex towards the wind*.

(3) In both cases above, the small plane should be set as far as possible from the main plane, and the planes should be set at positive angles with one another.

The damping effect is the same with the front disposition as with a back disposition, and therefore it is not necessary to consider again the theory of this.

Range of Travel of the Centre of Pressure on Bodies of Different Shapes

The amount of longitudinal equilibrium depends upon the rate of change of the centre of pressure with change of the angle of inclination.

We have already seen that a flat plane (1), Fig. 49, may be made longitudinally stable, owing to the fact that the centre of pressure approaches the forward edge with decrease of angle.

With a plane having the concave part downwards, as in (2), the centre of pressure approaches the forward edge until a certain angle is reached; a further decrease in the angle then causes it to travel backwards. It is therefore

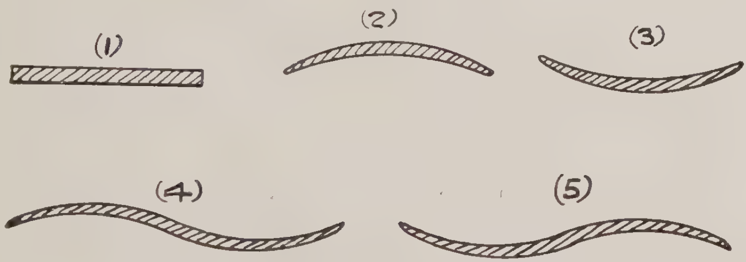


Fig. 49.—Sections of planes in relation to centres of pressure and automatic stability.

impossible to make the centre of pressure travel to both sides of the centre of gravity, and hence a plane of this shape cannot be made stable.

When a concavo-convex plane is turned into the position (3), the centre of pressure approaches the front edge continuously with decrease of inclination. The same change also takes place with the plane shaped as in (4). Thus, these shaped planes may be made stable. Plane (5), is unstable as in (2). (5) is unstable as in (2).

Manual and Automatic Control

In all the cases with which we have dealt so far, the stability has been automatic without any mechanical movement of the planes.

Now, the front or back plane may be angularly controlled by the operator, and thus the *travel of the centre of pressure may be governed.*

This system is known as fore-or-aft control, according to whether the controlling plane or "elevator" is in front or behind the main plane.

In some cases, controlling planes, which are cross-connected, are placed both in front and behind the main plane. This system is known as fore-and-aft control. It was first used by Sir Hiram Maxim on his machine of 1893-94. It was used with great success by Curtiss on the machine which won the first aerial Gordon-Bennett race. Sir Hiram's latest machine is also provided with fore-and-aft control, as this system gives the maximum controlling grip of the air for a minimum longitudinal length.

Automatic Control

Instead of the operator controlling the planes by hand, this may be done by automatic mechanism. This is known as automatic control.

There are two systems of automatic longitudinal control,—

(1) The gyroscopic, and
(2) The aerodynamic.

The first was invented in 1891 by Sir Hiram Maxim, and the second was also invented in the same year, and by an Englishman named Moy. These are described in Specifications, No. 19228/91 (Maxim), and No. 14742/91 (Moy), respectively.

In the first case, the longitudinal stability is maintained by means of a gyroscope, which resists a change of motion, and operates a mechanical relay, so as to throw into action a large power which operates the stabilising planes.

In the second case, a small vane is made to run in the air and to operate mechanism.

If the air acts above the plane, it is depressed, and, *vice versâ*, if below, it is raised.

The subject of automatic control will apparently have a great future, for, to use an engineer's expression, it will make the flying machine "fool-proof."

CHAPTER IV

Automatic Lateral Stability

We have, so far, only considered the longitudinal, or fore-and-aft, stability of a glider. Longitudinal stability, however, is not the only necessary condition for successful flight. It is necessary to provide means for making a

Fig. 50.—Diagram illustrating the various methods of obtaining lateral stability.

glider stable *laterally*—*i.e.*, along a line at right angles to the line of flight.

There are at least three well-defined means for doing this,—

(1) By the use of a dihedral angle between the wings.
(2) By the provision of a vertical plane or planes above the centre of gravity of the machine.
(3) By a suitable disposition of the centre of gravity.

We will take these in order,—

(1) If we take any ordinary sheet of paper and let it fall, it will roll over and over anyhow; but, if we bend the paper about the middle, it will fall straight down without turning over.

Now, the wings of a machine in flight are set at a certain angle relatively to the line of flight, as shown in Fig. 50, where A B is the axis of the machine and C D is the line of flight.

(1st Case). To simplify matters, let us assume that the planes are parallel with the axis of the machine, and that the machine is rotated about this axis. Let the axis of the machine when in flight be at an angle α, say,—

Thus, from Fig. 51, as the plane A C rotates to the

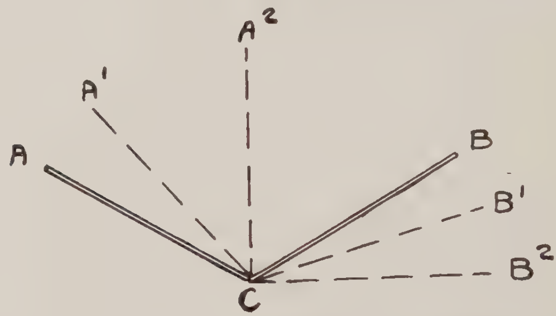


FIG. 51.—Diagram illustrating the various methods of obtaining lateral stability.

position A^1C, *its inclination* to the line of flight *will diminish* until, when it is vertical at A^2C, the inclination will become zero.

On the other hand, the plane C B will *increase its inclination* as it rotates to the positions CB^1, CB^2, and will be a maximum and equal to α when it is horizontal.

Now, the speed of the two wings relatively to the air is the same in both cases. The resultant air pressure will therefore act at the centre of both wings.

FIG. 52.—Diagram illustrating the various methods of obtaining lateral stability.

Also, the resultant force varies with the inclination of the plane, thus the force R^1 will diminish, and the force R^2 will increase as the rotation continues.

There is, however, a further increase of the force R^2, and a corresponding decrease of the force R^1, owing to the fact that the sum of the vertical components of R^1 and R^2, must always equal W. If they are not equal, the machine will fall faster until this is so.

Now, the effect of a greater falling speed is the

equivalent of an increase in the angle of inclination of the planes, and of the axis, to the line of flight, thus,—

The inclination is $=\alpha$ to horizontal path A B, but it is $=$

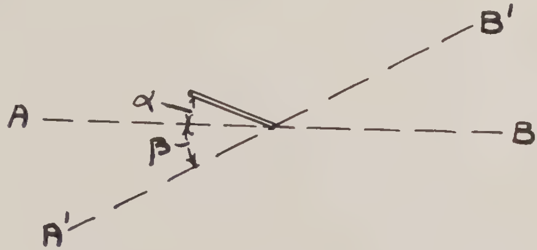


FIG. 53.—Diagram illustrating the various methods of obtaining lateral stability.

$\alpha+\beta$ to downward path $A^1 B^1$, therefore we see that, owing to this effect, the respective changes in R^1 and R^2 will be in the ratio of the relative angles, and not of the actual angles—*i.e.*, R^2 will be increased and R^1 decreased at a greater ratio than the variation in the actual angle would appear to warrant.

Then, if we take moments about the point C, we get,— Couple tending to restore the machine to equilibrium $=$ $R^2 \times a - R^1 \times a$. Where $(a)=$half length of wing. It follows that the maximum stability effect from the dihedral angle may be obtained by having a dihedral angle of 90°, then, when R^2 is a maximum, R^1 will be zero. This is not advisable, owing to other reasons.

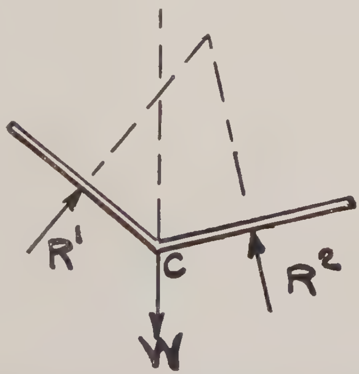


FIG. 54.—Diagram illustrating the various methods of obtaining lateral stability.

(2nd Case). We will now assume that the wings are inclined to the axis, and that the axis A B is horizontal.

If we rotate the machine about the axis, it will be seen that the inclination of the wings always remains the same.

Thus, if the path of the machine is kept *horizontal*, since the inclination remains the same, the *couple* introduced by each wing will be *equal and opposite*, and there will be no restoring force.

But, as the machine is rotated, since the horizontal components of R^1 and R^2 must equal W, it follows that the inclination of the path of the machine must be increased—*i.e.*, that the machine must fall faster along the line D C (Fig. 55).

This is, of course, *equivalent to setting the axis of the machine at an angle* α with the air. Therefore, when the axis is rotated, the inclination of the wing on the rising side to the relative wind is decreased, while that on the other side is increased.

Thus, as before, it is seen that a couple is introduced, tending to restore the machine to its normal position.

FIG. 55.—Diagram illustrating the various methods of obtaining lateral stability.

We have taken for the purpose of our argument the two extreme cases. It follows that a similar reasoning applies to every intermediate case.

It should be noted that the great objection to the use of the dihedral angle for obtaining lateral stability is, that the wedge-shape formation enables the machine to cut its way downwards through the air, and thus reduces the lift efficiency. The ideal shape for lift efficiency is undoubtedly the inverted dihedral angle.

(2) Lateral stability may also be obtained by means of a suitably disposed vertical plane.

The explanation of this is far more simple than the case of the dihedral angle.

If the upright plane is at right angles to the main plane, and above the centre of gravity of the machine, then, if the axis of rotation is inclined to the line of flight, as in Fig. 56 (a), it follows that the upright plane will gradually receive an increasing inclination, which will be at its maximum when it is horizontal.

Thus, a normal reaction R^1 will be introduced, which will form a couple tending to restore the machine to equilibrium.

It follows that an upright plane will *not* give lateral stability if it is so mounted that, when the machine is rotated laterally, it remains *parallel* to the line of flight.

(3) In the third case, the reaction R may be resolved vertically and horizontally.

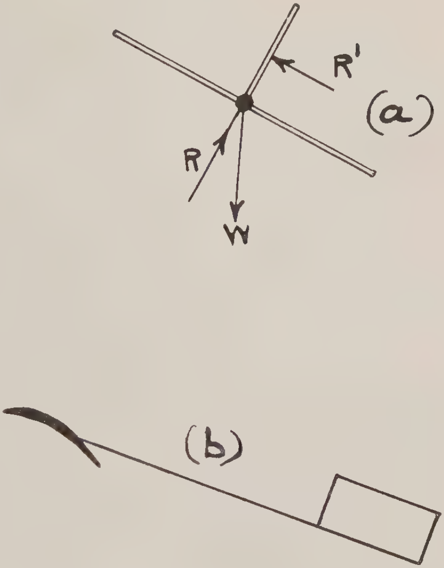


FIG. 56.—Diagram illustrating the various methods of obtaining lateral stability.

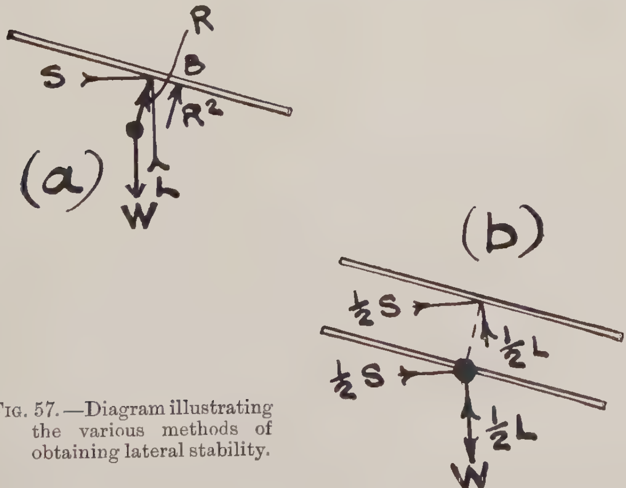


FIG. 57.—Diagram illustrating the various methods of obtaining lateral stability.

If the centre of gravity is below, then the vertical component L will equal W, and will form a couple tending to restore the machine to equilibrium.

The horizontal component S will cause the machine to run sideways. That is to say, the line of flight will be slightly inclined towards one side of the machine—*i.e.*, the centre of the reaction R will travel slightly towards that side to B, say, and thus still further increase the restoring couple.

Lateral Control (Manual and Automatic)

The lateral stability of a machine may be controlled by moving small side planes or "ailerons," or by warping the main plain so that the lower side may be given a greater inclination and lift. The aileron systems of lateral control appear to have been first invented by two Englishmen, Boulton and Harte, see 392/68 and 1469/70 respectively, and the wing-flexing device by the Wright Brothers.

The ailerons may be controlled automatically by means of pendulums and the like.

Yet another method of controlling a machine laterally is that proposed by the author, in which a vertical plane, placed above the centre of gravity of the machine, is warped or inclined to either side by the aviator.

CHAPTER V

Propellers

Since all the power of an engine is supplied through the propeller, it follows that the efficiency of a machine as a whole depends upon the efficiency of the propeller.

Thus, great attention should be paid to the design of a propeller.

If we take a wedge-shaped piece of paper, and wrap it round a cylinder, the upper edge will form a spiral, or helix (Fig. 58). If a horizontal radius is kept in contact with the spiral ABC, it will sweep out a spiral surface as it rotates around the centre.

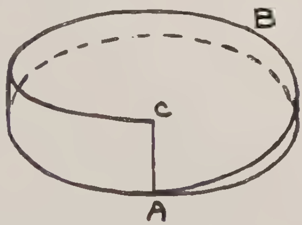


Fig. 58.—Diagram illustrating the principles of the screw propeller.

Fig. 59.—Diagram illustrating the principles of the screw propeller.

A propeller is formed by taking a portion of such a surface, as shown in Fig. 59, two blades being shown representing two separate spirals.

When such a propeller screws itself forward, the air yields and slips away. The axial speed of the propeller is therefore not so great as it would be if there were no "slip." If no slip occurs, the distance which a screw would move forward in one revolution is called the pitch, and = AC,

and the angle between the two sides is called the pitch angle.

$$\therefore \text{Theoretical speed} = \text{pitch} \times \text{revs. per min.}$$
$$\text{Actual speed} = \text{pitch} \times \text{revs. per min.} - \text{slip.}$$

If the pitch of every part of a screw is to remain constant, the inclination of the surface must increase as the boss is approached, as is shown in Fig. 60, for two points A and B.

The theoretical or maximum thrust at any given speed R (revolutions per minute) is given by the equation

$$\text{H.P.} = \frac{\text{Thrust} \times \text{speed}}{33{,}000} = \frac{\text{Thrust} \times \text{R} \times \text{pitch}}{33{,}000}$$

$$\therefore \text{Theoretical Thrust} = \frac{\text{H.P.} \times 33{,}000}{\text{R} \times \text{pitch.}}$$

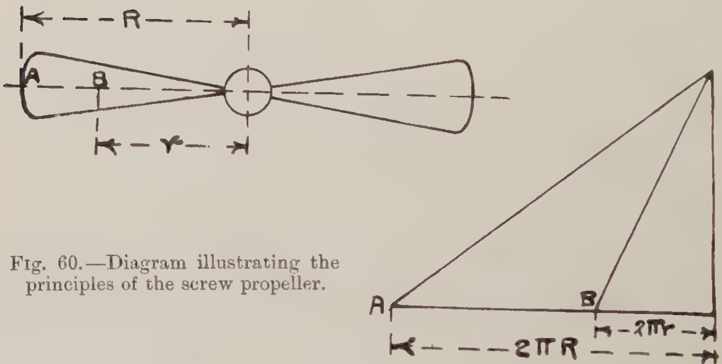


Fig. 60.—Diagram illustrating the principles of the screw propeller.

If we knew exactly how a propeller acted upon the air, we should readily be able to calculate its thrust.

In the early days of aeronautics, it was thought that centrifugal action took place, *i.e.*, it was thought that a great deal of the air was flung out radially from the circumference of the propeller, giving no effective reaction component.

Sir Hiram proved that this view was wrong, by surrounding a propeller with a wire, to which a series of short ribbons had been attached, and noting the direction of flow at every point. When his observations were plotted, the following diagram (Fig. 61) of the lines of flow was obtained.

In the author's steam line apparatus, ammonium chloride fumes were generated and allowed to pass into the air through fine jets, which were set at a known distance apart. The air was thus marked by bands of smoke, and from the photos, which are shown in Figs. 62 to 66 inclusive, it will be seen how the air flows about a propeller. Fig. 62

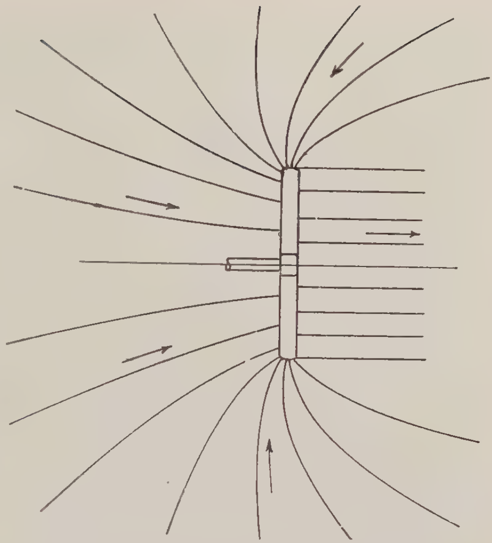


FIG. 61.—The flow of air about propellers.

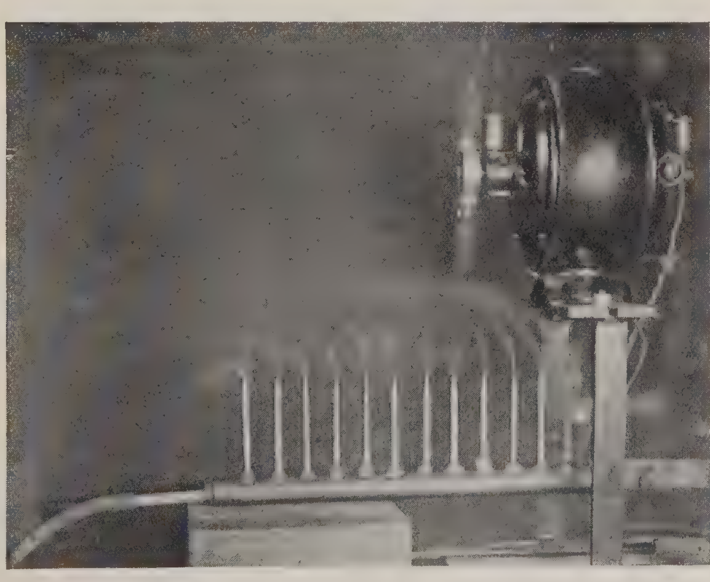


FIG. 62.—The flow of air about propellers.

Fig. 63.—The flow of air about propellers.

shows a flat-bladed brass propeller running at 1050 revs. per min. Fig. 63 shows the radial infeed on the same propeller, when running at 830 revs. per min. Figs. 64 and 65 show the wooden propeller which Sir Hiram Maxim found to give the best results. Fig. 66 shows an aerodynamical paradox which was discovered by Sir Hiram Maxim. The blade is shaped as shown in Figs. 67 and 68; Fig. 68 being an end view. This blade is mounted with the flat face towards the left of the photograph (Fig. 66). It was found that it drove the air away from the flat face in a cylindrical column, no matter in which direction it was rotated.

The explanation of this phenomena is given by Fig. 68. It will be seen that the

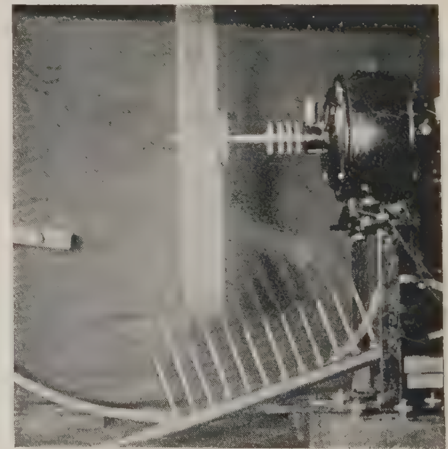


Fig. 64.—The flow of air about propellers.

air travels up the front incline and closely adheres while it travels down the back. Thus the air leaves the plane with a downward momentum impressed upon it, the reaction of which is represented by a thrust or a lift.

When the pitch angle of a propeller exceeded 45° at the circumference, Maxim found that centrifugal or fan-blower action occurred, the air being driven off in a cone.

We may assume that the air leaves a propeller in a cylindrical column when the pitch angle is less than 45°.

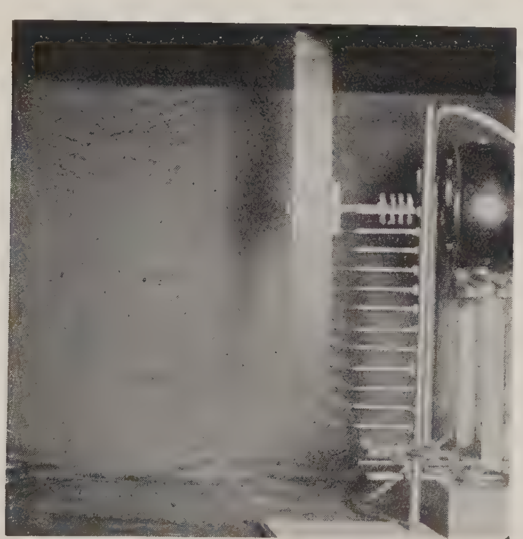


FIG. 65.—The flow of air about propellers.

The following deductions may therefore be made:—

(1) If the diameter of a propeller = D, and the velocity of a column of air, when it is running at a certain speed = V, then the momentum given to the column of air = M V = thrust, where M = mass of air driven per second; the kinetic energy given to the air or work lost = $\frac{1}{2}$ M V^2.

Then the ratio of $\frac{\text{thrust}}{\text{H.P.}}$, that is, thrust per

$$\text{horse-power} = \frac{M\,V}{\frac{1}{2}M\,V^2} = \frac{2}{V} \qquad (a).$$

Now, suppose we reduce the speed of the

propeller to one-half. Since only half as much air is acted upon, thrust $= \frac{1}{2} M \times \frac{1}{2} V$.

$$\text{Work done} = \frac{1}{2}\left(\frac{1}{2} M\right)\left(\frac{1}{2} V\right)^2 = \frac{M V^2}{16},$$

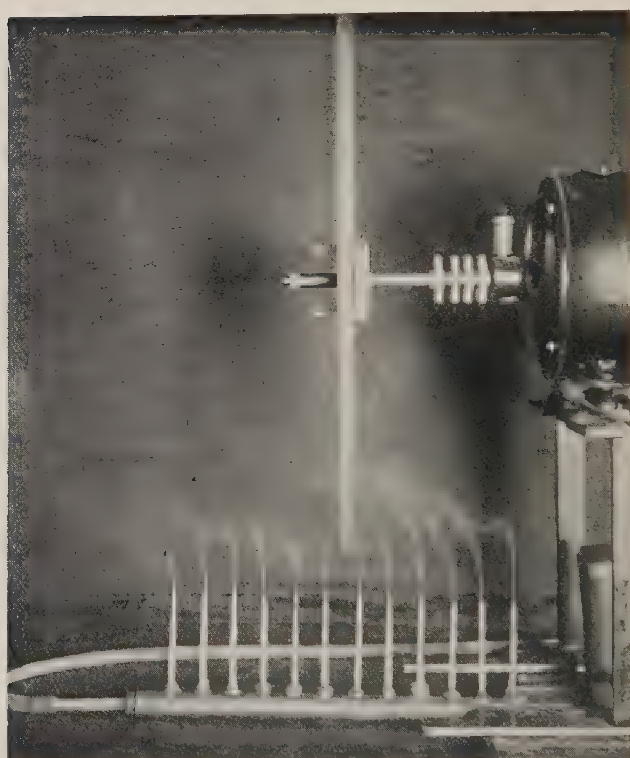


FIG. 66.—The flow of air about propellers.

$$\therefore \frac{\text{thrust}}{\text{work done}} = \frac{\frac{M V}{4}}{\frac{M V^2}{16}} = \frac{4}{V} \quad . \quad . \quad . \quad (b),$$

i.e., just double that of (a).

This means that the *efficiency of a standing propeller* (*i.e.*, the ratio of the thrust to the horse-power) *varies inversely*

as the speed. This at first sight appears to be paradoxical, but it is fully borne out in practice.

(2) Now, let us consider two propellers, having diameters D and 2 D. Let m = mass of unit

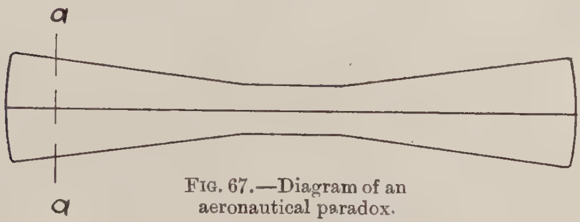


Fig. 67.—Diagram of an aeronautical paradox.

vol. of air. If they both drive a column of air at the same velocity V, we see,—

$$\text{Thrust of first} = \text{M V} = \left(\frac{\Pi}{4} \text{D}^2 \times \text{V} \times m\right) \times \text{V}.$$

$$\text{Thrust of second} = \left(\frac{\Pi}{4} (2\,\text{D})^2 \times \text{V} \times m\right) \times \text{V}.$$

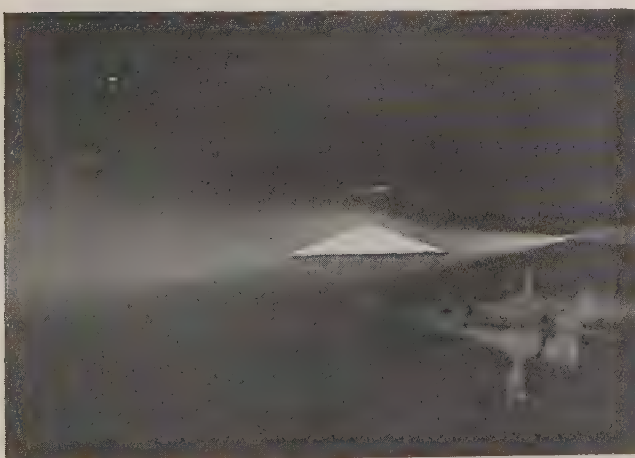


Fig. 68.—The stream line flow about an aerodynamical paradox.

$$\frac{\text{Thrust of second}}{\text{Thrust of first}} = \frac{\frac{\Pi}{4} \times 4\,\text{D}^2 \times \text{V}^2 \times m}{\frac{\Pi}{4}\,\text{D}^2 \times \text{V}^2 \times m} = 4.$$

That is, by doubling the diameter, we get four times the thrust.

In the same way, by tripling the diameter we shall get nine times the thrust.

Therefore, the *thrust of propellers* having the *same pitch*, and running at the *same speed*, varies as the *square of the diameter.*

(3) Suppose a *constant* thrust is desired from propellers of various diameters, D, 2 D, 3 D.

In the first case,—

$$\text{Thrust} = \left(\frac{\Pi}{4} D^2 \times V \times m\right) V.$$

$$\text{Work done} = \tfrac{1}{2} M V^2 = \tfrac{1}{2}\left(\frac{\Pi}{4} D^2 \times V \times m\right) V^2.$$

In the second case,—

$$\text{Thrust} = \left(\frac{\Pi}{4} (2 D)^2 \times V_1 \times m\right) V_1.$$

But the thrusts are to be equal,

$$\therefore \left(\frac{\Pi}{4} D^2 \times V \times m\right) V = \left(\frac{\Pi}{4} 4 D^2 \times V_1 \times m\right) V_1.$$

$$\therefore V^2 = 4 V_1^2 \;\therefore V = 2 V_1.$$

$$\therefore V_1 = \tfrac{1}{2} V.$$

$\therefore$ work done in the second case $=$

$$\tfrac{1}{2}\left(\frac{\Pi}{4}(2 D^2) \times \tfrac{1}{2} V \times m\right)(\tfrac{1}{2} V)^2.$$

$$\therefore \frac{\text{work done first}}{\text{work done second}} = \frac{\tfrac{1}{2}\left(\frac{\Pi}{4} D^2 \times V \times m\right) V^2}{\tfrac{1}{2}\left(\frac{\Pi}{4} 4D^2 \times \tfrac{1}{2} V \times m\right) \tfrac{1}{4} V^2} = \frac{2}{1}.$$

That is to say, the work required to drive a stationary screw is halved by doubling the diameter. In the same way it can be shown that, by tripling the diameter, the work required is divided by three.

Or, in general language,—

The *work required* to drive a *standing propeller* or helicopter, thrust being constant, *is inversely proportional to the diameter.* Thus, the larger the propeller, the greater the weight which can be sustained for a given horse-power.

In 1809, Sir George Cayley demonstrated that, if it were possible to construct a screw having a diameter of 200 feet, then a man would be able to support his weight by means of his own power.

Further, as Sir Hiram has said, if the diameter were increased to 2000 feet, then the power of a man would sustain the weight of a horse, and conversely, if the diameter were reduced to 20 feet, then the power of a horse would be required to sustain the weight of a man.

The next problem which presents itself is to devise a formula giving the variation of thrust and horse-power with the speed and diameter of a propeller.

Let D and 2D = diameters of two screws
N = revs. (in any unit of time).

Now, consider the effect of speed. If we double the speed, we shall give the air *twice* the velocity, and we shall also deal with *double* the amount, *i.e.*, we shall give it four times the momentum, and therefore shall get four times the thrust.

The work done in the first case will be $\frac{1}{2}MV^2$, and in the second case $\frac{1}{2}(2M)\,(2V)^2 = 4MV^2$, *i.e.*, eight times as much.

If we treble the speed, then, from the same reasoning, we shall get nine times the thrust, and the work done will be twenty-seven times as much.

$$\therefore \text{ the thrust} \propto N^2$$
$$\text{and work done} \propto N^3.$$

Let us now assume that the pitch of both propellers is the same, *i.e.*, that they both drive a column of air at the same velocity when running at the same speed.

Since the diameter of the second is double the diameter of the first, the amount of air driven off by the second is four times that driven off by the first, because the diameter of the column of air is doubled, *i.e.*, the thrust of the second is four times the thrust of the first.

Similarly, if the diameter of the second is three times the diameter of the first, the thrust will be nine times that of the first; therefore, with screws of equal pitch, the thrust varies as the square of the diameter, and clearly, the work done varies in the same proportion.

$$\text{Hence, thrust} \propto N^2D^2;$$
$$\text{work done} \propto N^3D^2.$$

Now, propellers of different diameters, and having the same pitch, are not similar. Propellers are *similar* when the pitch angle is the same.

If the pitch angle is constant, then the pitch varies as the diameter, *i.e.*, the velocity given to the column of air varies as the diameter, therefore, if we double the diameter of the screw, and take equal areas of the column in each case, since the velocity is doubled, double the amount of air will be acted upon, and each particle will receive double the momentum, therefore, the thrust will be four times as great.

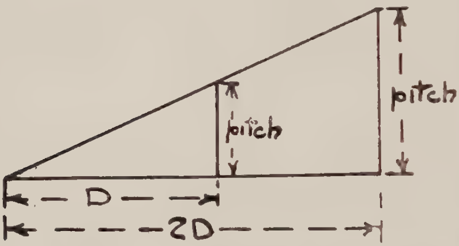


FIG. 69.—Diagram illustrating the principles of the screw propeller.

Similarly, if the diameter is trebled, the thrust will be nine times as great, *i.e.*, the thrust per unit area of the column is proportional to the *pitch squared*, *i.e.*, to *diameter squared*.

Gathering our results, we can write :—

$$\text{Thrust} \propto N^2D^2 \times D^2 \propto N^2D^4$$

or, introducing a constant K :—

$$\text{Thrust} = KN^2D^4 \quad . \quad . \quad . \quad . \quad . \quad (1).$$

Now, with regard to the work done, if we take again equal areas of the column in each case, the diameters being D and 2D, we get, since the velocity of the column is $\propto$ to pitch, and pitch is $\propto$ to diameter :

$$\frac{\text{Work in first case}}{\text{Work in second case}} = \frac{\frac{1}{2}(m \times V)V^2}{\frac{1}{2}(m \times 2V)(2V)^2} = \frac{1}{8}$$

When diameters are D and 3D :

$$\frac{\text{Work in first case}}{\text{Work in third case}} = \frac{\frac{1}{2}(mV)V^2}{\frac{1}{2}(m \times 3V)(3V)^2} = \frac{1}{27}$$

i.e., work varies as the cube of the diameter, and

$$\text{work} \propto N^3 \times D^2 \times D^3 \propto N^3D^5,$$

or, introducing a constant C :

$$\text{Power} = CN^3D^5 \quad . \quad . \quad . \quad . \quad (2).$$

If, therefore, we determine the thrust and horse-power for a screw at any one certain speed, we can determine K

and C (the constants in the equation (1) and (2),) and hence, we can calculate the thrust and horse-power for any speed of any *similar* propeller. (By similar, is understood every propeller having the *same* pitch angle, and the same relative shape of blade.) These formulæ appear to have been amply verified by practice, and also by mathematical investigation.

Walker and Alexander's Experiments

Propellers 30 ft. in diameter of the tandem or Mangin type.

A. 4 blades, 6 ft. wide.
B. 2 blades, 6 ft. wide.
C. 4 blades, 3 ft. wide.
D. 4 blades, 3 ft wide, but 6 ft. radius of blade removed.
E. 4 blades as A, but at 21° angle.

A to D blades at angle of $12\frac{1}{2}°$

E gave greatest thrust per 1 horse-power.

As a result of these experiments, it was found that

(1) Thrust varies as square of revolutions.
(2) Horse-power varies as cube of revolutions.
(3) Thrust per horse-power varies inversely as revolutions.

Renard and Krebes.

Work done W Kgm. metres	Revs. per mins.	Thrust T.	$\frac{T^3}{W^2}$
27	17	8	·7
70	24	15	·69
150	32	26	·78
242	35	35	·73
364	40	47	·78
617	48	64	·69

It will be seen that $\frac{T^3}{W^2}$ is approximately constant. The relation $\frac{T^3}{W^2}=$constant, is merely another way of stating the results obtained by Alexander and Walker.

These experiments are a striking justification of the methods of reasoning previously used.

The beneficial effect of *engaging as much air as possible* (because of the relations of the formulæ,

$$\text{Force} = MV, \text{ and Work lost} = \tfrac{1}{2}MV^2),$$

is well illustrated by the following examples :—

(1) If a revolving stationary propeller is subjected to a cross current of air, its thrust is increased, and the greater the speed of the cross current, the greater the thrust.

(2) When a propeller is first started, its thrust is greater than when it has been running some little time, and the air has got into a steady state of motion. This excess of thrust will depend entirely upon the speed of acceleration. If a propeller is started very quickly, the excess thrust is great.

(3) When a running propeller is given an axial motion, its thrust does not fall off in the same ratio as the slip velocity. Thus, if, when the screw is stationary, the slip velocity is, say, 60 miles per hour, then, at an actual forward velocity of 40 miles per hour, the slip velocity is 20 miles per hour. Although the slip velocity has been reduced from 60 miles an hour to 20 miles an hour, *i.e.*, to one-third, the thrust would not be reduced to one-third; in fact, with Sir Hiram's big machine, under the above conditions, it was proved that the thrust did not drop off much up to a slip speed of between 60% and 70% of the theoretical speed. With the high-speed propellers, as used on flying machines, it may be assumed that a similar state of affairs holds.

We may therefore write,

$$\text{Thrust} = \cdot 7 \times \text{Theoretical Thrust.}$$

$$= \cdot 7 \times \frac{\text{H.P.} \times 33{,}000}{V}$$

where H.P. = actual horse-power applied, V = axial velocity.

Therefore, if, from the formula

$$T = KN^2D^4,$$

we determine the stationary thrust at a certain speed, then, for most well-made high-speed propellers, we may

assume that this thrust will not greatly fall off up to a speed of ·7 of the theoretical axial speed.

The fuller formulæ for an axially moving propeller, has been deduced by Captain Ferber:—

$$F = h\,(\alpha r - \alpha^1) n^2 D^4 \qquad (1).$$

$$T = (h^2 \beta r - \beta^1) n^3 D^5 \qquad (2).$$

$$V = n\,P(1 - r) \qquad (3).$$

$$h = \frac{\text{pitch}}{\text{diam.}} = \frac{P}{D} \text{ or } \textit{relative pitch.}$$

$$r = \text{relative slip}$$

$$= \frac{n\,P - V}{n\,P}$$

$$\therefore V = n\,P(1 - r). \quad \text{Equation (3) above.}$$

F = Thrust.
T = Power.
V = Velocity.

α, α^1, β, β^1, are coefficients which can be determined (*see L'Aviation* by Captain Ferber).

TABLE SHOWING VELOCITY AND THRUST CORRESPONDING WITH ONE HORSE-POWER

Velocity in miles per hour	Thrust in Pounds
1	375
5	75
10	37·5
15	25
20	18·8
25	15
30	12·5
35	10·7
40	9·4
45	8·3
50	7·5
60	6·3
70	5·4
80	4·7
90	4·2
100	3·75

CHAPTER VI

HELICOPTERS—METHOD OF SETTING OUT PROPELLERS—POSITION OF PROPELLERS

A SCREW may be used, not only for propelling a machine, but also for supporting it. A machine supported by a screw or screws is called a *helicopter*. The problem before the designer of a helicopter is, clearly, how to obtain the maximum lift with the minimum power. Since the function of a helicopter is not to screw itself up rapidly into the skies, but, merely, to support itself with a fair margin for special circumstances, the problem of a helicopter is that of the stationary revolving screw.

It was seen in problem (3) that the *power* required to drive a screw *varies inversely* as the *diameter* if the thrust is constant. Therefore the efficiency of a helicopter depends directly on the diameter. Almost the whole theory lies in the fact that for maximum efficiency the maximum of air must be engaged. A hovering helicopter is unable to avail itself of the great source of efficiency of the aeroplane, *i.e.*, of running into undisturbed air, and of leaving the air that has already been disturbed.

A French mathematician once proved that a goose exerted 1 horse-power in flying. His reasoning was briefly this: He determined the speed at which a goose would fall with wings outstretched. Then he reasoned that the work done by a goose is that required to lift its weight with the same vertical velocity with which it would fall downwards. The result deduced was, of course, erroneous. The same reasoning, however, would have been perfectly correct if applied to a helicopter, the vertical velocity being substituted *by the slip* of the screw and the area by area of the screw circle.

It will be seen from this why it is that a helicopter is so inefficient compared with an aeroplane. The efficiency of a helicopter may be made to approximate to that of an aeroplane if it is given a lateral motion.

Let the lateral motion $= v$. Also let $V =$ velocity of the tips of the blade due to the speed of revolution. Then the velocity of the tip of the blade on one side is $V + v$, and on the opposite side $V - v$. Now, lift is α to velocity squared, therefore, the lifts of two opposite sides are $\alpha\,(V + v)^2$ and $(V - v)^2$. That is, the lift on one side is greater than on the other, and there is a cross torque introduced tending to rotate the screw about an axis parallel to the line of motion. This cross torque would be a very serious matter in the case of a large rapidly-moving machine. It could be counteracted by introducing another screw at the side of the first, revolving in an opposite direction to the first; but this would not overcome the difficulty of taking up the side-thrust in the bearings and the shafts. Thus, to make the vertical shaft strong enough to resist the bending movement introduced, it would require to be made much stronger and heavier than otherwise.

The Importance of Engaging as much Air as possible

Sir Hiram Maxim has long realised the importance of engaging as much air as possible, and thus, in his early machine, he used two screws, each having a diameter of 17 feet 10 inches. If the machine would have allowed it, he would have made them 24 feet in diameter.

The Wright Brothers use two wooden propellers, each of 8 feet 6 inches in diameter. That is, they engage between six and seven times more air per horse-power than on the Farman machine. The flight of the Wright machine at Rheims was not so steady and imposing as that of several other makes, but there is no gainsaying the fact that the machine was very efficient as regards weight carried per horse-power. Thus, although the Wrights' machines were only a few miles an hour slower than the fastest, they certainly did not have more than half the horse-power of the successful machines. If there had been a suitable horse-power handicap, the results of the Rheims meeting would probably have been very different. People are apt to forget this. In the early days of their experiments, the ratio of the air engaged per horse-power to that of the Farman machine was as 10·5 : 1. As a result, with an engine only capable of developing 14 horse-power, they flew with a passenger. No other aviator has approached this.

The air engaged per horse-power, *i.e.*,—

$$\frac{\text{area of screw circle sq. ft.}}{\text{horse-power}}$$

is a useful quantity in showing the propeller efficiency of a machine.

Machine	Air engaged sq. ft. per horse-power
Farman	·77
Maxim (old)	1·7
„ (new)	4·4
Wright (ordinary)	4·5
„ (first flyer)	8·1

Method of setting out the drawing of a propeller, the pitch P and diameter D being given. Set off line AD $= \frac{1}{2}$D, and DX at right angles to AB $= \frac{P}{2\pi}$ (Fig. 70). Then angle XAD is the pitch angle at the circumference, and the pitch angle for any other point on the line AD may be determined by drawing a line from that point to the point X.

We will suppose, as an example, that the blade is to be of wood formed in six strips, and that in side view it is to subtend the same width. From the point A, set off EA and FA, each $= \frac{W}{2}$, where W = true width of blade at the tip. Draw lines 1, 7, through E and F parallel to AD, and divide the subtended width into six parts by the lines 1, 2, 3, 4, 5, 6 and 7. To get the corresponding lines in end elevation, with E as centre and $\frac{D}{2}$ as radius, strike off the circle KAL. Through B draw a horizontal CB, then AB is the true width between any pair of lines. CB is the width between in side elevation, and AC is the width between in end elevation. Therefore, with width AC mark off on either side of A the points 1, 2, 3, 4, 5, 6 and 7, and join to centre E. Draw horizontals across from the points 1, 2, on the arc KAL to the corresponding lines on the left-hand figure, and draw the curve MAN through the points of intersection. The lines EF, GH and IJ, are true widths

of the blade at the various radii on the line AD, and the section which the blade is to have at these points should be set off on these lines.

To get the outline of the blade in side elevation, project from the ends of the width EF, GH, etc., on to the corresponding curves MN, OP, etc., and join up. In the case

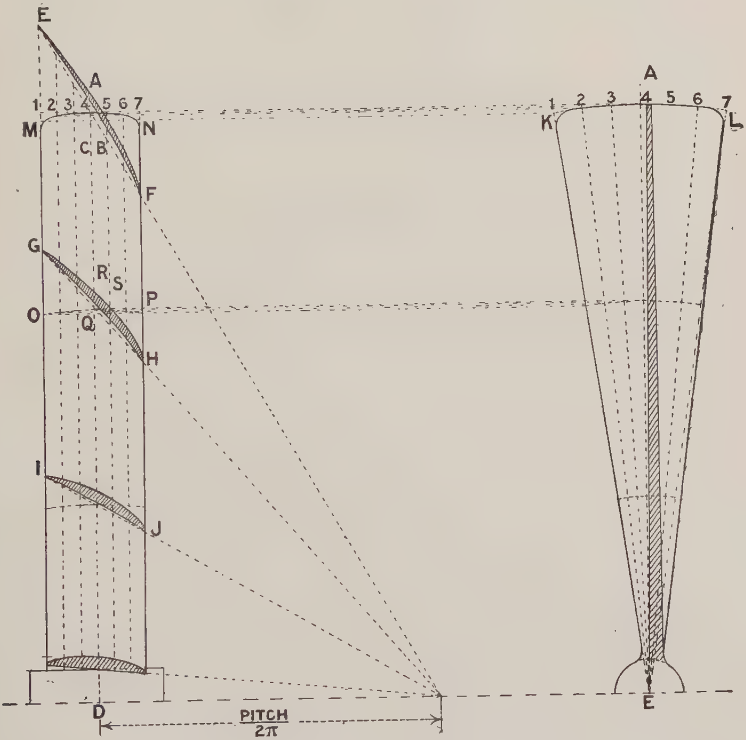


FIG. 70.—Method of setting out a propeller.

under consideration, the sides will be straight lines from the fundamental hypothesis. To get the outline of the blade in the end elevation, project across from the points MN, OP, etc., on to the corresponding arcs KL, etc., and join up. The end section of the blade at the middle may be obtained by marking off QS and QR, etc., from the corresponding point in the end elevation. Any shape or form of blade may be set out in like manner.

Propellers, the Effect of Position of

A most important consideration to the designer is as to the best position of the propeller, or propellers, and the various advantages and disadvantages of different dispositions.

In the case of the monoplane, as it was found difficult to arrange the propeller behind, it was tried in front. A most extraordinary effect was thereby obtained, which was unaccountable at first.

It was found that a machine, instead of lifting, say, $2\frac{1}{2}$ lbs. per square foot at 40 miles an hour, lifted fully 5 lbs. per square foot.

On the R.E.P. monoplane, a lift of as much as $6\frac{3}{4}$ lbs. per square foot has been obtained.

From Fig. 54 it was seen that the air is sucked in from the front of a propeller and all round the sides, and that it is driven off at the back approximately in a cylindrical column.

Thus, for two reasons, it follows that the lift per unit area of a plane will be increased by placing the propeller in the front—(1) because the speed of the plane relatively to the air is increased, and (2) because more air is engaged.

With regard to the first point, since the lift of an aeroplane *is* proportional to the square of the velocity, if v = velocity of machine, and V = average velocity of the current of air driven off by the propeller, then the average velocity of the machine relatively to the air $= V + v$.

$$\therefore \frac{\text{Lift of plane without propeller}}{\text{Lift of plane with propeller}} = \frac{v^2}{(V+v)^2}.$$

With regard to the second point, the importance of engaging as much air as possible has already been realised, in view of the fact that it is more efficient to engage a large amount of air and give it a small velocity, rather than to engage a small amount and give it a high velocity, as is shown by the two relations,—

Force $= M \times V$. Kinetic energy $= \frac{1}{2} MV^2$ where V is the change of velocity.

Thus, owing to the sucking effect of the propellers, more air is engaged than would otherwise be the case, and thus, for the second reason, the lift is increased.

There is one very great disadvantage, however, of this front disposition of the propeller—*i.e.*, the effect of the

wind is to blow the machine backwards, or, in other words, the propeller pulls the machine forwards and the reaction blows it backwards. The effective propelling force is the difference of these two forces.

Now, the power required to drive an aeroplane, if the angle is kept constant, is proportional to the cube of the velocity. The power required to drive all non-lifting parts of the machine is also proportional to the cube of the velocity.

In the case of an ordinary aeroplane driven through the air, since the weight is constant, then, if the speed is doubled, the inclination may be reduced. Thus, the power required to obtain the supporting force varies at a considerably less rate than the cube of the velocity; but the power required to drive the obstructing parts is always proportional to the cube of the velocity.

Now, in the case of the monoplane, with the propeller in front, the *head* resistance is increased out of proportion to the actual speed of the machine, because of the backward wind. Also, instead of keeping the area constant, and reducing the angle, as in the illustration just given, the area is reduced, and the inclination is kept constant. Thus, if the speed is doubled, instead of following Langley's law, and reducing the thrust to one quarter and the power to one half, the thrust per unit area is quadrupled, and, if the area is proportionally reduced, the thrust will remain constant, and thus the power required will vary as the square of the speed instead of inversely as the speed.

It follows that this disposition of the propeller is not so efficient as other dispositions, although it enables the span to be reduced.

Thus, we find that, whereas the span of a monoplane with the propeller in front may be made not greater than that of a biplane, the horse-power required to drive it is considerably more than that of a corresponding biplane.

It is probable that, in the future, use may be made of this lifting effect without forward motion. Two distinct schemes for obtaining lift without lateral motion have been proposed :—(1) Bleriot's, (2) Porter's.

(1) Bleriot's method consists "in applying to aeroplanes, propellers with horizontal shafts, so that they can drive the air against the in-

clined wings of the apparatus so as to sweep their surface, and to submit them to elevating forces similar to those to which they are submitted with the ordinary apparatus when running at a high speed."

The apparatus may be propelled by two tractor screws *a* (Fig. 71), which are each mounted on short horizontal shafts *b*. These shafts are normally parallel to the axis of the machine, but for starting they are swung round at right angles to the axis, as shown in the sketch, so as to neutralise each other's pull and to cause a compression underneath and a suction over each wing.

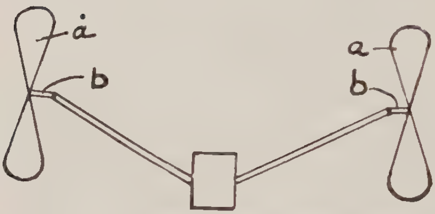


FIG. 71.—Bleriot's method of lifting without motion of translation.

In a modification (Fig. 72), a series of propellers may be placed along the front edge of the plane, thus :—

For starting, the machine is tied to a fixed point, and the propellers are revolved at sufficient speed to lift the machine. When a sufficient altitude has been obtained, the machine is released and starts its journey.

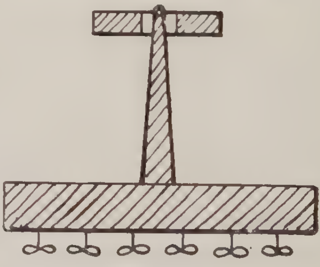


FIG. 72.—Bleriot's method of lifting without motion of translation.

A similar device has been proposed by Mr Alexander for utilising the gusts of a wind for supporting a machine. The wind always blows in short gusts, and, therefore, has a considerable internal energy which is available for use.

In Mr Alexander's apparatus, a number of free propellers are placed along the front plane, as in Bleriot's device, so that when the gust exceeds the average velocity, the speed of the propellers is accelerated. When the gust stops, the momentum of the propellers creates a temporary artificial draught until the gust again blows. Thus it is possible

to avail oneself of the change of velocity of the wind to assist in supporting an aeroplane.

(2) In Porter's method, the air is flung outwards by centrifugal force against an annular aeroplane.

CHAPTER VII

Calculations relating to the Desing of a Flying Machine

In the design of a vessel, the first consideration is to obtain sufficient buoyancy, the second is to obtain stability.

Let G be the centre of gravity of the vessel, H the centre of gravity of displaced fluid when floating normally.

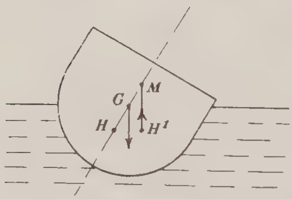


Fig. 73.—Diagram illustrating the restoring couple on a floating vessel.

If the vessel is given a small displacement, let H_1 = centre of gravity of the displaced fluid in the new position. Then draw a vertical through H_1 cutting G H in M. Then M is the meta centre.

If M is above G, the vertical pressure of the displaced fluid introduces a couple tending to restore the vessel to its original position.

One of the most important problems in naval architecture is to secure the ascendency under all circumstances of the meta centre over the centre of gravity.

The couple resisting displacement $\propto$ to the distance of the meta centre above the centre of gravity.

Hence, the stability of the vessel depends on this distance.

Flying machines have points of similar importance. If the points do not fulfil certain conditions, then nothing in the world can make a machine fly or prevent it being anything else than a death-trap.

As we shall use two principles in our calculations, it may be well to consider them first.

(1) With regard to moments,—

If we have two or more parallel forces, X, Y, etc., acting on a body, the resultant $= X + Y$, etc.

To find the point at which this force acts, we can take moments.

$$\text{Thus, } X \times b + Y(a+b) = R(b+x);$$

$$\therefore b + x = \frac{Xb + Y(a+b)}{R};$$

$$\therefore x = \frac{Xb + Y(a+b)}{R} - b.$$

(2) With regard to couples,—

A couple introduced anywhere may be balanced by a couple of opposite sign placed anywhere in the same plane.

Take moments about any point P. Then we get

$$X(a+q) - Xq + Yr - Y(b+r)$$
$$= aX + qX - Xq + Yr - Yb - Yr$$
$$= aX - bY = 0.$$

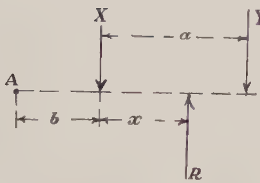


FIG. 74.—Diagram illustrating the calculations relating to the design of flying machines.

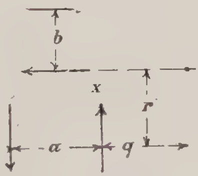


FIG. 75.—Diagram illustrating the calculations relating to the design of flying machines.

An aeroplane has four main forces acting upon it:

(1) The weight acting through the centre of gravity.
(2) Total lift acting through the centre of pressure.
(3) Total resistance acting through the centre of resistance.
(4) Total thrust acting through the centre of thrust.

In the ideal condition, when these four forces act through a common point and are equal, there is equilibrium, thus:—

Now, if the thrust and resistance are not in line, the couple introduced may be balanced by introducing a couple of opposite sign, formed by arranging the lift and the weight out of line, thus—

Thrust above resistance.

(*a*) If Thrust $\times a =$ Lift $\times b$, there is equilibrium.

If the engine stops in a machine in which the equilibrium

is obtained in this way, let us consider what happens. The thrust will equal nothing, and the system will be unbalanced, and the lift-weight couple will tend to rotate it, *i.e.*, to cause the front of the machine to rise and turn completely over.

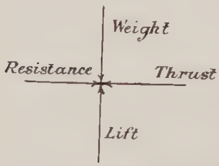


FIG. 76.—Diagram illustrating the calculations relating to the design of flying machines.

(*b*) If thrust below resistance. Then TR couple may be balanced by placing W in front of L. If T is cut out as before, the WL couple will tend to rotate the machine by causing the head to dive down.

Thus, although machines in which one of the above state of affairs holds, may be made to fly while the engine continues to run, the stoppage of the engine would bring disaster.

The author has seen a good many engines stop in mid-flight, and the result in some cases has shown that sufficient attention has not been paid to this point.

Now, according to the disposition and arrangement of the screws, engine, and various parts of the machine, we can fix the centre of gravity, the centre of resistance, and the centre of thrust, but we cannot fix the centre of lift.

In the case of the inclined plane, we have seen that the centre of pressure travels forwards as the angle of inclination is decreased.

In the case of the curved plane, the centre of pressure,

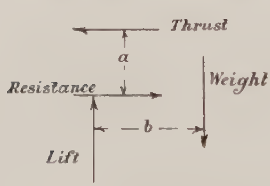


FIG. 77.—Diagram illustrating the calculations relating to the design of flying machines.

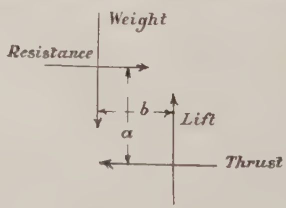


FIG. 78.—Diagram illustrating the calculations relating to the design of flying machines.

or lift, travels forwards with decrease of inclination up to a certain amount, when it travels backwards with a further decrease of inclination.

As a result, we are only able to balance the forces for a particular angle, preferably the angle of inclination

most generally taken, and extraneous means must be provided to counteract the couple introduced by the change of the centre of pressure.

The Wrights use a plane in the front, which rides parallel with the wind under normal conditions, and gives no lift, but which can be warped in either direction as required.

Thus, the controlling planes are sometimes lifting, and sometimes forcing the machine downwards.

By placing controlling planes both fore and aft, the fore plane may be used when the centre of pressure travels backwards, and the back plane when the centre of pressure travels forwards.

This is the system which Sir Hiram used in his early

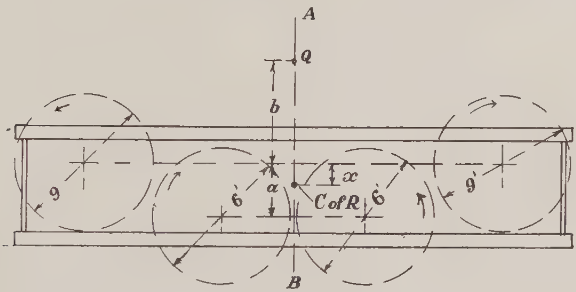


FIG. 79.—Diagram illustrating the calculations relating to the design of flying machines.

machine, and it is interesting to note that the most successful and steadiest flyer at Rheims, *i.e.*, the Curtiss machine, had this system of control. There appears to be a considerable future for this system.

To illustrate the method of calculating the position of the four points, let us take an example. As it appears probable that, in the future, more than two propellers will be used, suppose we take four to illustrate the method.

The theoretical speed of all the propellers should be the same, *i.e.*, the product revs. $\times$ pitch should be equal. If this is so, we may assume with a fair degree of accuracy that the thrust of each propeller $\propto$ to the area of the screw circle.

$$\text{Total thrust} = \text{K}\frac{\Pi}{4}(81 \times 2 + 36 \times 2).$$

To find the centre of thrust. We know it will lie

along the line AB, because the propellers are in pairs, and are equidistant in pairs from the line AB, therefore, we may take moments about any point Q.

$$\text{Then } K\frac{\Pi}{4}(2\times 36)(a+b)+K\frac{\Pi}{4}(2\times 81)b$$

$$=K\frac{\Pi}{4}(2\times 81+2\times 36)(x+b)$$

$$\therefore\ 36a+36b+81b=117x+117b$$

$$\therefore\ x=\frac{36a}{117}$$

therefore, we know the *point* at which the thrust will act.

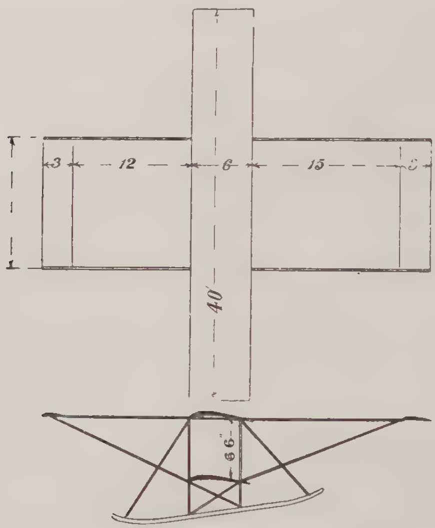


FIG. 80.—Diagram illustrating the calculations relating to the design of flying machines.

TOTAL LIFT

At an angle of 1 in 10, and at a speed of 40 miles an hour, a well-shaped plane will lift 2·25 lbs. per square foot. Owing to the wind of the propeller, the tail will lift double this amount,

$$\therefore \text{ Total lift}=(40\times 6\times 2+13\times 3)\,2{\cdot}25$$
$$+13\times 3\times 4{\cdot}5$$
$$=\underline{1345 \text{ lbs.}}$$

Now, the next point is to calculate the total resistance, and the centre of resistance. The head resistance of main planes at an angle of 1 in 10 will be about one-ninth the lift, and $= \frac{1}{9} \times 480 \times 2{\cdot}25 = \underline{120 \text{ lbs.}}$

Resistance of front plane $= \frac{1}{9} \times 39 \times 2{\cdot}25 = \underline{9{\cdot}75 \text{ lbs.}}$

Resistance of back plane $= \frac{1}{9} \times 39 \times 4{\cdot}5 = \underline{19{\cdot}5 \text{ lbs}}$

Resistance of wooden struts

$$8 \times \frac{1}{2 \times 12} \times 6{\cdot}5 \times \text{resistance lbs. per sq. ft.,}$$

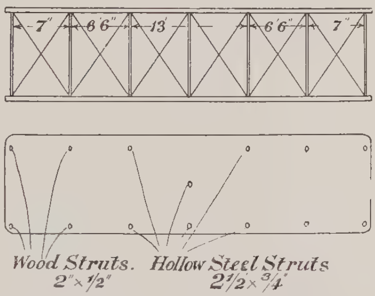


FIG. 81.—Diagram illustrating the calculations relating to the design of flying machines.

$$\text{and } R = {\cdot}0013V^2$$

for elliptical struts having major diameter = two minor diameters

$$= {\cdot}0013 \times 40^2.$$

Therefore, resistance of wooden struts

$$\frac{8}{24} \times 6{\cdot}5 \times {\cdot}0013 \times 40^2$$

$$= \underline{4{\cdot}5 \text{ lbs.}}$$

Resistance of five iron struts

$$\frac{5 \times 6{\cdot}5}{16} \times {\cdot}0013 \times 40^2 = \underline{4{\cdot}22 \text{ lbs.}}$$

We may proceed in the same way with all the other parts of the machine, and adding them together we shall get the *total resistance.*

To obtain the *centre of resistance,* we take moments about any point A. Then

$$R \times x = 9{\cdot}75 \times a + 120 \times b + 8{\cdot}77 \times c + 19{\cdot}5 \times d$$

and so on,

$$\therefore x = \frac{9{\cdot}75\,a + 120\,b + 8{\cdot}77\,c + 19{\cdot}5\,d, \text{ etc.}}{9{\cdot}75 + 120 + 8{\cdot}77 + 19{\cdot}5, \text{ etc.}}$$

Therefore, x being known, the position of the propellers

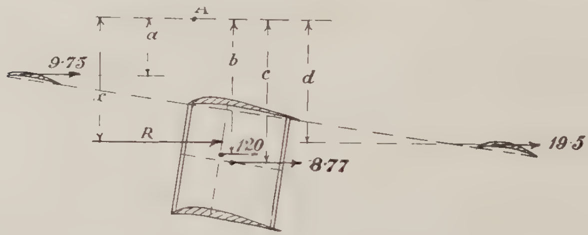


FIG. 82.—Diagram illustrating the calculations relating to the design of flying machines.

may be fixed, so that the centre of thrust and the centre of pressure may be in suitable positions.

CENTRE OF GRAVITY AND TOTAL WEIGHT

To obtain the total weight and the centre of gravity, we first obtain the weight of the separate parts, by calculation, or otherwise. Thus,—

Weight of wooden struts — Spruce 31·25 lbs. per cubic ft.

$$= 8 \times 6{\cdot}5 \times \frac{{\cdot}829 \times \frac{1}{2} \times 2}{144} \times 31{\cdot}25 = \underline{9{\cdot}36 \text{ lbs.}}$$

Weight of steel struts = 18·3 lbs.

Total weight of struts = 18·3 + 9·36 = 28 lbs. say.

Weight of main planes (double surfaced)—

Total volume of wood = 3935 cubic inches.

$$\text{Weight of wood} = \frac{3935}{1728} \times 31{\cdot}25 = 71 \text{ lbs.}$$

Weight of silk, 3 oz. per square yard = 10·8 lbs.

Total weight = 71 + 10·8 = 81·8 lbs.

say 90 lbs.

In the same way, we may calculate the weight of the

fore and aft planes and of the other parts of the machine. Then taking moments about A, we get

$$\text{Total weight} \times x = 180x\,a + 28x\,b + 20x\,c$$

$$\therefore x = \frac{180a + 28b + 20c, \text{ etc.}}{180 + 28 + 20, \text{ etc.}}$$

In our present state of knowledge, the determination of the centre of lift is not easy, because no reliable data is to hand giving the centres of pressure of various surfaces

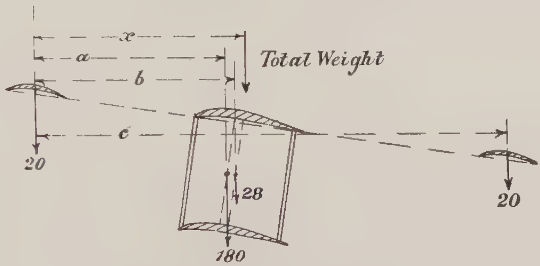


FIG. 83.—Diagram illustrating the calculations relating to the design of flying machines.

and bodies when inclined at various angles. It is, therefore, best to construct a small model of the machine, and determine the centre of lift at any angle, by placing it in a wind tunnel. Or a small paper glider may be made, and the weight adjusted until the best glide is obtained. Then we may assume that the centre of gravity of the figure corresponds with the centre of pressure.

If, when the centre of lift has been determined, it is found not to be in the right position relatively to the centre of gravity, then the centre of gravity should be changed by altering the position of the engine, or operator, etc.

The above calculations, although simple, are perhaps of greater use to the practical man than the higher mathematics of the aeroplane.

CHAPTER VIII

Laboratory Instruments and Apparatus

It is interesting at this stage to study briefly the instruments and apparatus which are used for determining experimental data connected with the science of aeronautics.

This apparatus may be divided roughly into four classes :—

(1) Anemometers, or instruments for measuring the speed or the distance travelled through the air.
(2) Aerodynamical balances.
(3) Propeller-testing apparatus.
(4) Wind-tunnels and whirling-tables to enable the bodies being tested to be subjected to a current of air.

(1) *Anemometers* may be divided into two types,—

(*a*) Rotary vane, screw, or windmill type.
(*b*) Pressure type, in which the speed is recorded by measuring the thrust or pressure of the air.

(*a*) The rotary-vane anemometer is provided with an extremely light aluminium vane, very delicately mounted, so that it is rotated by the slightest motion of the air. This vane is connected, by means of gearing with a meter, which records the number of revolutions made by the vane. The instrument is graduated by the makers to record the number of feet of air passed over by the instrument. If the distance travelled is divided by the time taken, the resulting quotient gives the velocity.

(*b*) There are various types of pressure anemometers.

In the anemometer, invented by Sir Hiram Maxim and shown in Fig. 84, two bell-crank levers are pivoted to a weather-vane, and a spiral tension spring is connected to the two opposing arms. A horizontal rod is pivoted to the upper arms of the bell-crank levers, and is provided with a vertical disc of known area. A pointer is con-

nected to one of the bell-cranks. The instrument may be graduated to read either the pressure or the velocity of

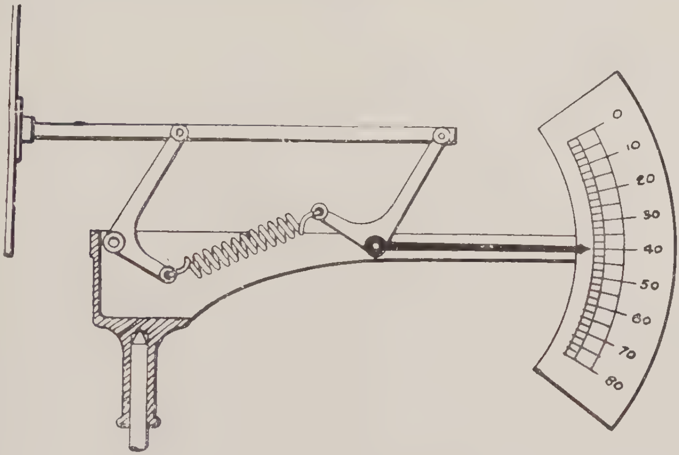


FIG. 84.—Maxim's anemometer.

the wind, the pressure and velocity being connected by the formula $P = \cdot003\,AV^2$.

A simple and extremely accurate method of measuring the speed is by means of a Pitot tube in conjunction with a sensitive water-gauge. The tube A (Fig. 85) has a thin-lipped orifice facing the current, and the tube B, for measuring the static pressure of the current, has a conical end with small holes perpendicular to the axis. The difference in pressure $= h$ in the two tubes is measured by a water-gauge.

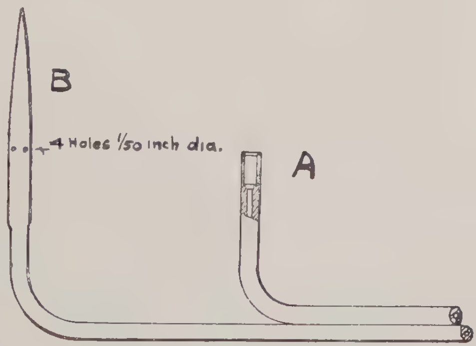


FIG. 85.—Pitot tube.

The velocity v is connected with the head h by the formula

$$v = k\sqrt{2gh}$$

where k is a constant, which does not differ greatly from unity. ($k = 1{\cdot}03$, Dr Stanton).

(2) *Aerodynamic balances* are of numerous types, and may be employed for a large number of different purposes,

Thus, the variation of the lift, with the inclination of a plane, may be determined by means of a simple piece of apparatus due to Lord Rayleigh.

In a modification of Lord Rayleigh's apparatus, three vanes are mounted on a frictionless spindle, each vane being set at 120° with the other. The vanes are of equal area, and are set at precisely the same distances from the centre.

If two vanes are both inclined at the same angle, and the remaining plane is set so as to tend to twist the apparatus in the opposite direction, the angle of this plane may be adjusted until it balances the torque of the two planes.

A means of finding the relation between the torque—*i.e.*, the lift of inclined planes—is thus provided.

Lord Rayleigh found that the maximum torque, or lift, with flat planes, occurs when the inclination is about 27°.

The same apparatus may be used to compare the relative lifts of inclined-curved planes.

We can also determine the relative values, as regards lift, of any two shapes of planes, by means of a similar device, in which the two planes are balanced or weighed against one another, a standard flat plane being used as a permanent member.

Since we know, from exact experiment, the lift of the flat plane at various angles, a very ready and reliable means is provided of testing the lift of a certain plane by a comparison with that of a known plane.

The drift and various other data connected with aeroplane and aerocurves may be obtained by balancing two planes about an axis at right angles to the direction of motion.

(3) *Propellers* should be tested when running (a) without axial motion, and (b) with axial motion.

(a) The static tests may be made by suspending the propeller and driving mechanism from above, and measuring the deflection and horse-power consumed when running at various speeds. The thrust may then be obtained by finding the force required to obtain the same deflections.

To obtain the thrust on the dirigible balloon "La

France," Colonel Renard swung the whole cage from the roof by means of a parallel suspension, as shown in Fig. 86.

Welner used the apparatus shown in Fig. 87.

In the Walker-Alexander tests, in which propellers of 30 feet in diameter were used, the thrust was recorded by means of the pull on a spring balance (Fig. 88).

(*b*) Propellers may be tested under axially running conditions by means of a wind tunnel or whirling-table.

In the first case, the propeller is placed in a current of air having a known velocity, and the readings connecting thrust, horse-power and revolutions are determined. This method does not greatly commend itself, in view of the fact that the field of a propeller is considerably greater than the diameter, and also that it does not permit tests being made when the propeller is not axial to the current of air.

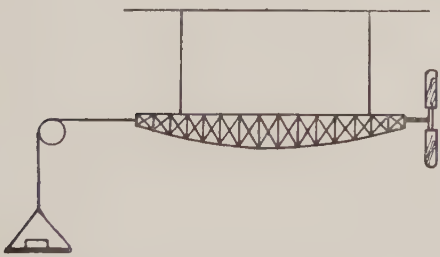


Fig. 86.—Static test of propellers. (Col. Renard.)

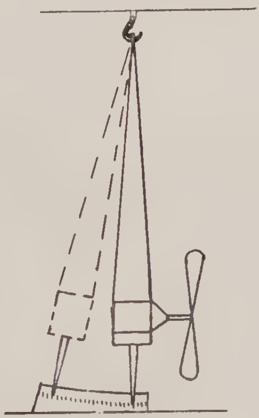


Fig. 87.—Static test of propellers. (Welner.)

In the second case, the propeller is mounted in any axial position required, at the end of a radial arm projecting from a rotating vertical shaft, and the readings connecting thrust, horse-power and revolutions are taken and plotted. The devices for enabling these readings to be obtained are numerous and ingenious.

(4) Wind tunnels and whirling tables.

The *whirling table* consists of a vertical rotating shaft carrying a radial arm, at the end of which the propellers, planes or bodies to be tested are suitably mounted.

In Sir Hiram Maxim's apparatus (Fig. 89), a fixed vertical steel shaft *a*, 6 inches in diameter, was mounted in a pedestal *b*, firmly grounded in concrete. This shaft was embraced by two pine planks *n*, 2 inches thick, between which were mounted the two members *h* of the radiating arm. The weight of the rotating parts was carried on a ball race *u*. The members *h* were of Honduras mahogany with their edges sharpened off, and were prevented from twisting by means of a tube *j*, 12 feet long, to the arms of which bracing wires were connected. The circumference of the circle around which the aeroplanes and propellers travelled was exactly 200 feet. The power was trans-

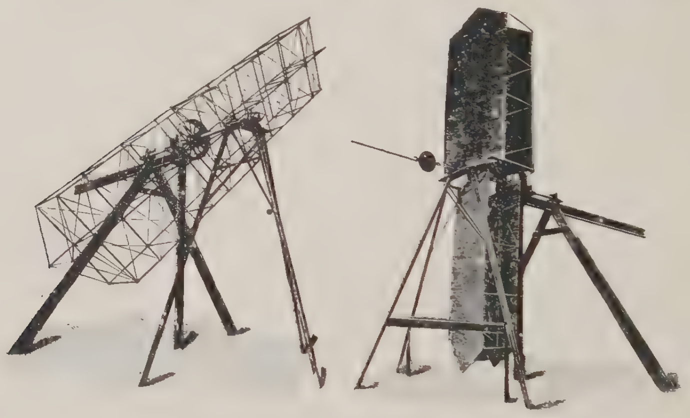


FIG. 88.—Static test of propellers. (Walker-Alexander.)

mitted from the engine to the propeller through a shaft *f*, bevel wheels, vertical shaft, pulley and belt *i* running through the arms *h*.

The operation was as follows:—The aeroplane *g* to be tested was mounted on a double parallel-motion linkage so that its inclination to the air always remained the same throughout the experiment. Upon starting the engine, the propeller caused the radial arm to travel at any desired velocity up to 90 miles per hour. The thrust of the screw caused the screw shaft to travel longitudinally against the action of a spring. This motion was transmitted to the pointer *o* by means of a fine wire. The pointer travelled over a graduated scale, thus enabling the thrust to be read at sight. The lift of the aeroplanes was determined by placing weights or shot in the pan *r* until the lift was

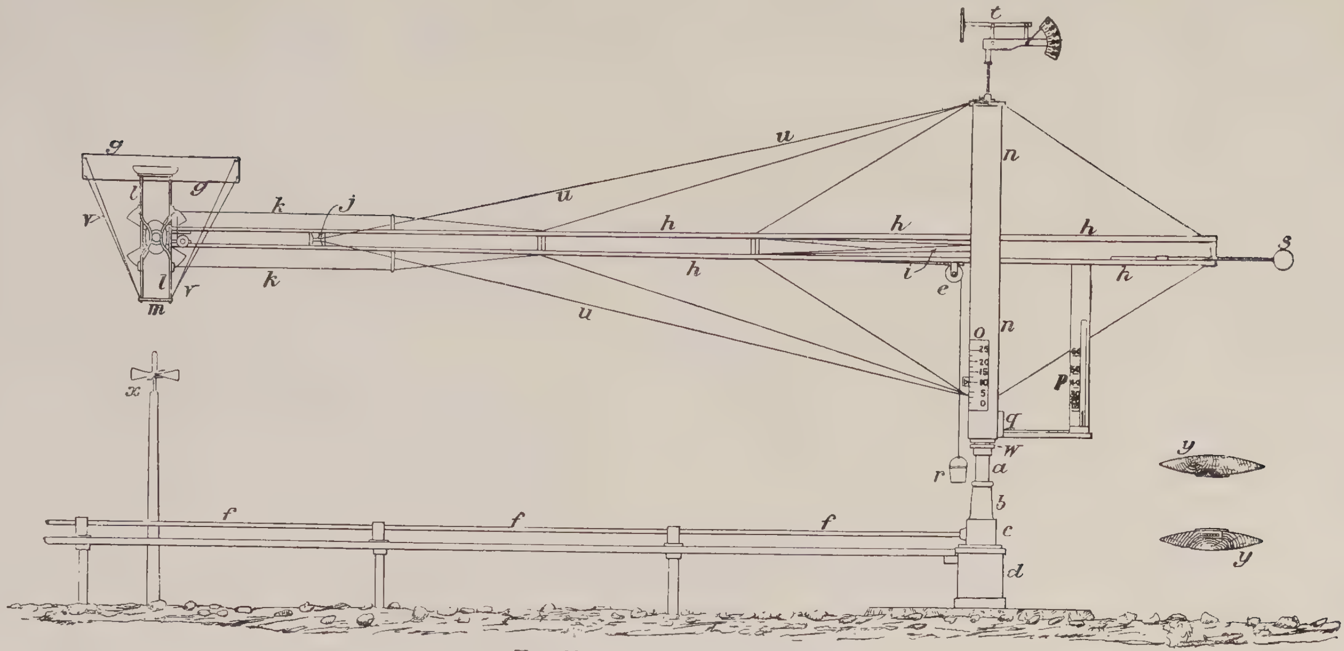


FIG. 89.—Whirling table. (Maxim.)

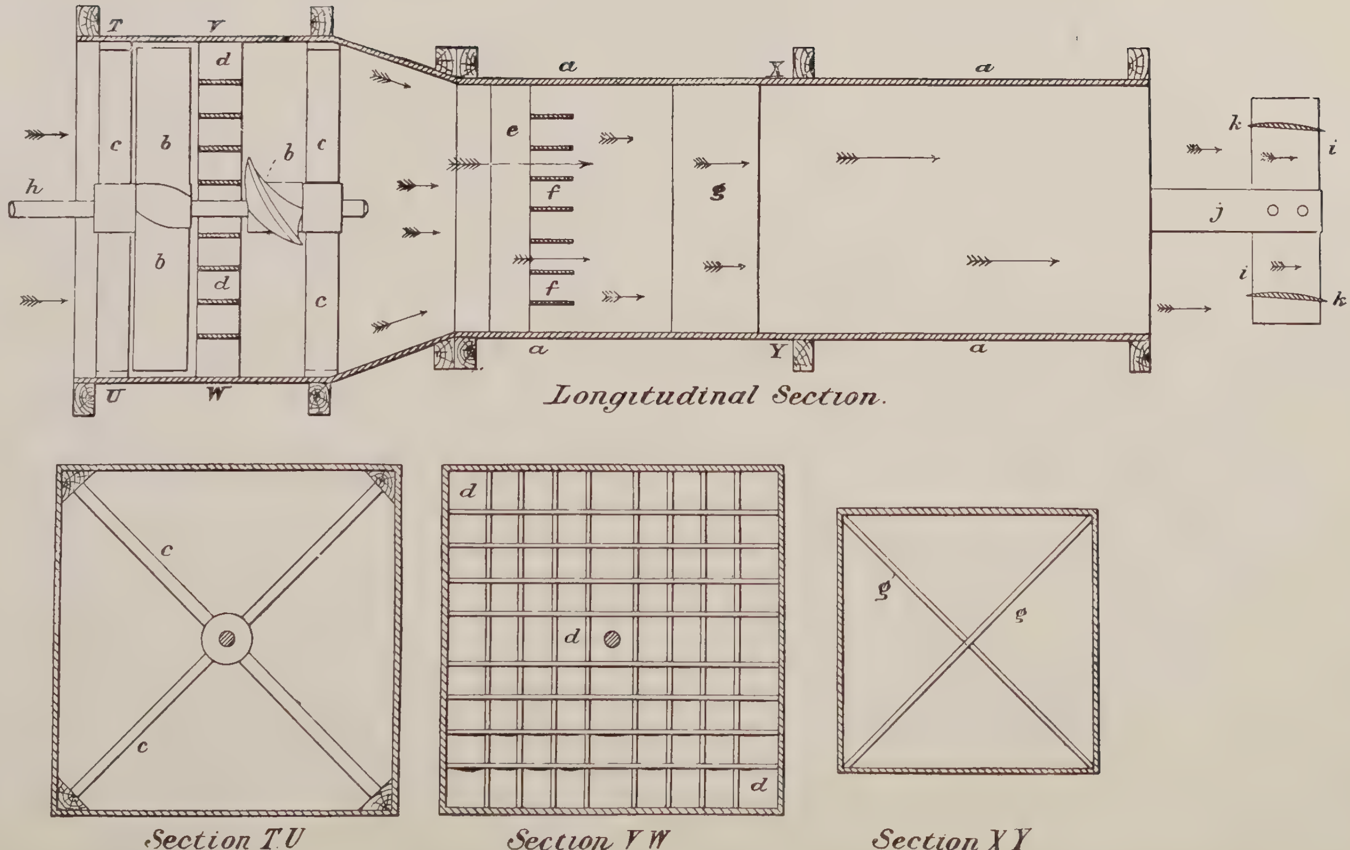


Fig. 90.—Wind tunnel. (Maxim.)

balanced. Then the actual lift was obtained, when the machine was stationary, by finding the pull required to lift the aeroplane against the weight of the pan r. The

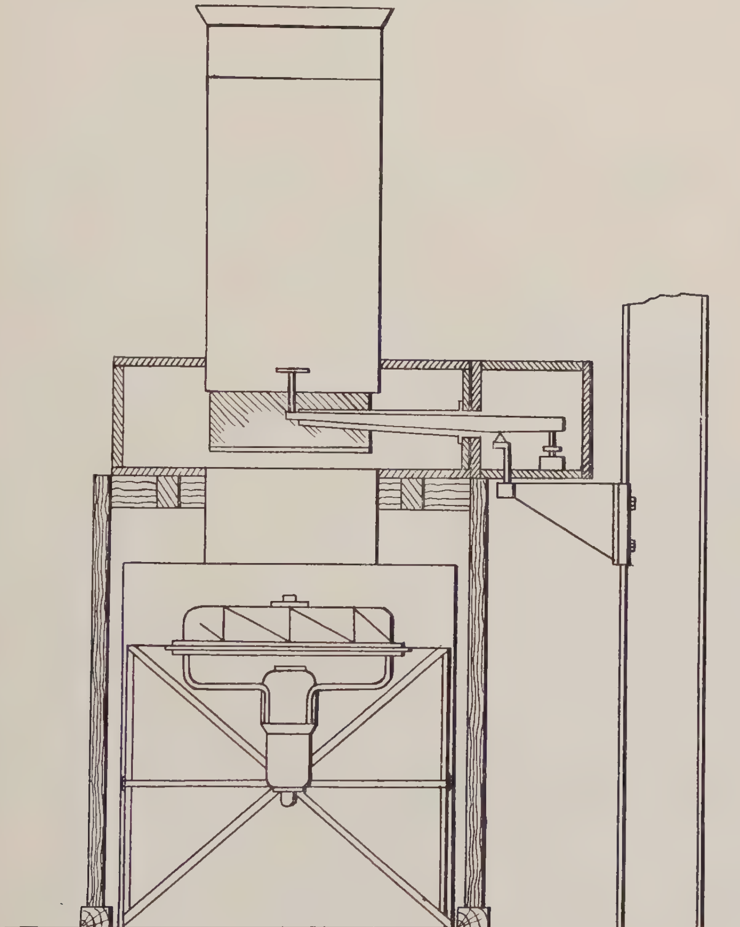


FIG. 91.—Wind tunnel. (Stanton.)

speed at which the propellers and aeroplanes were travelling was read by means of the centrifugal gauge p. The power transmitted to the propellers was recorded by means of a sensitive direct-transmission hydraulic dynamometer.

Thus, all the readings required, relating to aeroplanes and propellers, could be taken.

The *wind tunnel* consists of a tube, passage or tunnel, through which air may be forced or drawn by means of rotating fans, steam jets, or the like.

The tunnel may be vertical or horizontal. Sir Hiram Maxim used a horizontal tunnel (Fig. 90), in which the small part *a* was 12 feet long by 3 feet square inside, and the large part was 4 feet square. Two wooden screws *b* were mounted on a shaft *h* in the large part. The bearings of the shaft were supported by the diagonals *c*. Horizontal slats of wood *d* between the screws, and vertical and horizontal slats *e*, *f*, and diagonal boards *g*, were provided to prevent rotation of the air column. The lifts and drifts of aerocurves and other bodies were measured by means of a double system of parallel-motion linkage.

Dr Stanton used a wind tunnel (Fig. 91), in which the current was vertical and downwards. An electrically-driven fan, 2 feet 6 inches diameter, mounted in a box, 4 feet square, drew the air through a channel, 2 feet diameter by 4 feet 6 inches long. The pressure of the air on the test pieces was weighed by means of a delicate beam provided with a jockey weight and dash-pot.

CHAPTER IX

Types of Machines

Biplanes

Maxim's first machine, which was built and experimented with in 1893-4, was a biplane, having fore and aft control, *i.e.*, the longitudinal equilibrium of the machine was maintained by means of horizontal rudders placed before

Fig. 92.—Maxim's first biplane.

and behind the main planes. The spread of the planes was 105 feet. These planes were in three portions. The centre portion carried the whole of the machinery, and the other portions were set at a dihedral angle, as shown in Figs. 92 and 93, to give automatic lateral stability. The total supporting area was 4000 square feet, and the weight was between 7000 and 8000 lbs. The machine lifted on one occasion fully 10,000 lbs.

Propellers (2) wood, 17 feet 10 inches diameter driven by two compound steam-engines, each of 180 horse-power.

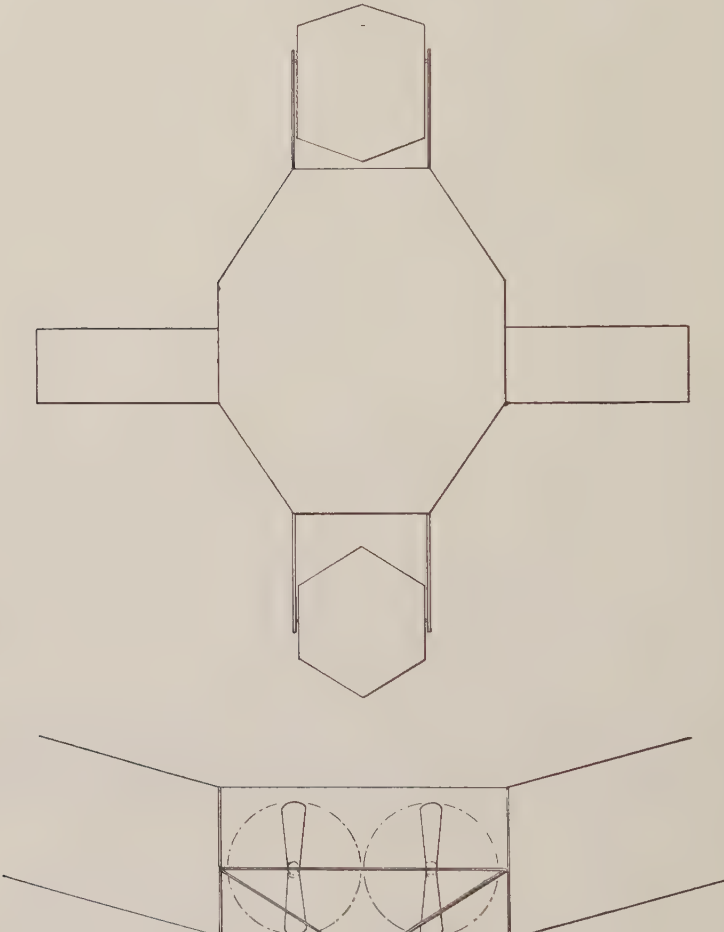


FIG. 93.—Drawings of Maxim's first biplane.

Maxim's second machine (Figs. 1 and 94) is a direct lineal descendant of the first type. The main planes are again divided into three portions, with the outer portions raised so as to give lateral stability. The machine is

provided with fore and aft biplane elevators, each 13 feet 6 inches by 3 feet. The main planes are 44 feet spread by 6 feet 6 inches width and 6 feet 6 inches apart.

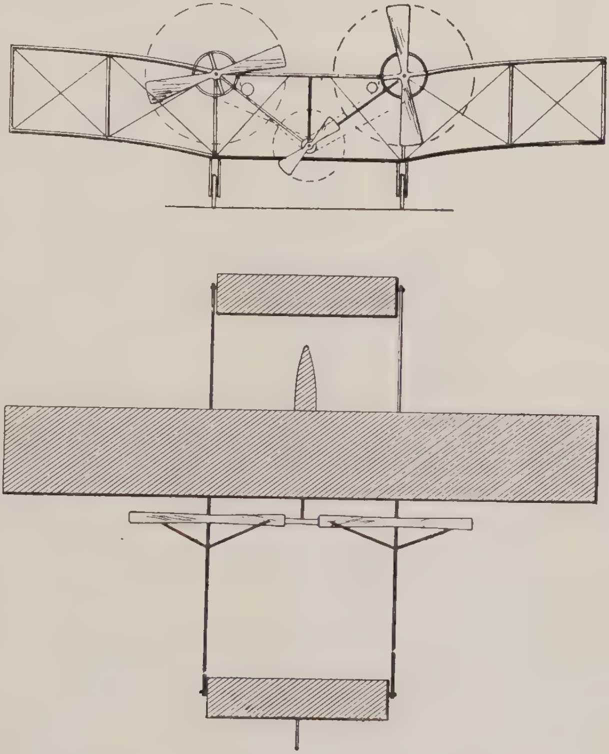


Fig. 94.—Drawings of Maxim's second biplane.

There are three propellers, two 11 feet $3\frac{3}{4}$ inches diameter, and one 5 feet diameter, driven by a 50 horse-power engine. Total supporting area, 734 square feet.

Wright (1905)

The Wright machine (Fig. 95) is a biplane, having two elevators in the front set at a *negative angle* with the main plane. These elevators ride parallel to the wind under normal conditions, and may be warped upwards or downwards to elevate or depress the machine. Two

vertical rudders are provided at the back of the machine for steering. The machine is controlled laterally by the combined use of the vertical rudders and warping wings. The rear corners of the main planes are cross connected so that a downward motion of one corner causes an upward motion of the other corner. The camber of the main planes is 1 in 20, the maximum rise being one-third width from the front edge. The total area of the machine is 594 square feet, and the weight in order of flight is 1200 lbs. Thus, the machine supports 2 lbs. per square foot.

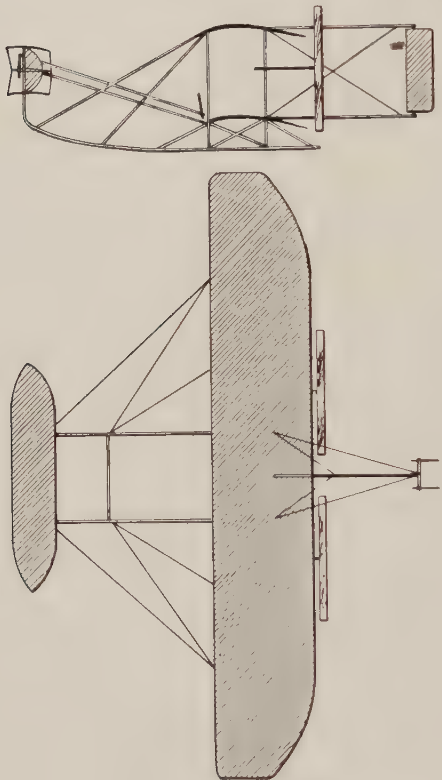


FIG. 95.—Drawings of the Wright biplane.

The gliding angle is about 1 in 8.

Main planes 41 feet by 6 feet 8 inches by 6 feet 2 inches apart.

Elevators (2) 15 feet 6 inches by 3 feet by 3 feet apart, and 10 feet 8 inches in front.

Rudders (2) 5 feet 10 inches by 2 feet, and 6 feet 8 inches behind.

Propellers (2) Wood, 8 feet 6 inches diameter, 550 revs. per min. Pitch angle, 25 degrees.

Curtiss

This very successful one-man biplane (Fig. 96), is provided with fore and aft control, as in Maxim's machines.

The front elevator is a biplane 6 feet by 2 feet, and 12 feet in front of the main planes. The back elevator is a single plane, 6 feet by 2 feet, and 12 feet behind the main planes. The main planes are 28 feet 9 inches span by 4 feet 6 inches wide by 5 feet apart. Camber 1 in 17. One of the features of the machine is in the position of the

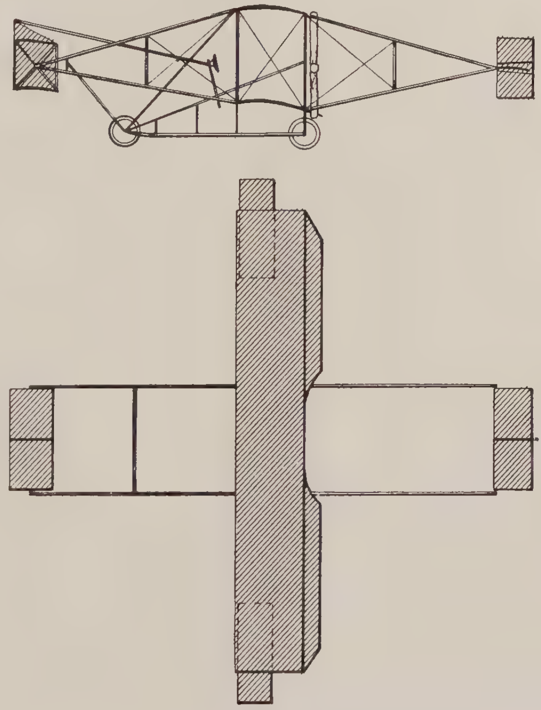


FIG. 96.—Drawings of the Curtiss biplane.

ailerons (6 feet by 2 feet), which are mounted between the main planes with the outer portions *projecting beyond* the extremities of the main planes. The machine is steered by a vertical triangular rudder in the front, and a fixed vertical plane is provided at the rear, to give an anchorage on the air for steering.

Weight in flying order = 550 lbs.
Total supporting area = 250.
Weight supported per square foot = 2·2 lbs.

FIG. 97.—The Curtiss' machine in full flight.

One propeller, 6 feet 6 inches diameter by 5 feet pitch, running at 1200 revolutions, and driven by an engine of 30 horse-power.

Voisin

The Wright Bros. began their experiments in 1900 by constructing a "glider." In 1903 they applied a motor to their machine, and made the first power flight. In 1905 they flew 24 miles in 38 minutes. These experiments, which are now well authenticated, were conducted in secret, and Europe was sceptical.

However, inspired by these accounts, experimenters were busy, and in October 1906 Santos Dumont made the first official flight. He was followed by Farman and Delagrange using machines constructed by Voisin Frères.

The Voisin machine (Fig. 98) is a biplane having a fixed box-tail and a front elevator. Side curtains are generally provided between the main planes to add to the lateral stability. Ailerons are generally not provided, the machine being controlled laterally by means of the vertical rudder mounted in the box-tail.

The main planes are 32 feet 10 inches span, by 6 feet 7 inches wide, by 6 feet 7 inches apart:

The tail planes are 7 feet 11 inches long, by 6 feet 7 inches wide, and are placed 13 feet 4 inches behind the main planes.

The front elevator is formed of two portions pivoting together, each 6 feet 11 inches long by 3 feet 3 inches wide, and is placed 4 feet 4 inches in front of the main planes.

The propeller is a metal one, 7 feet 6 inches in

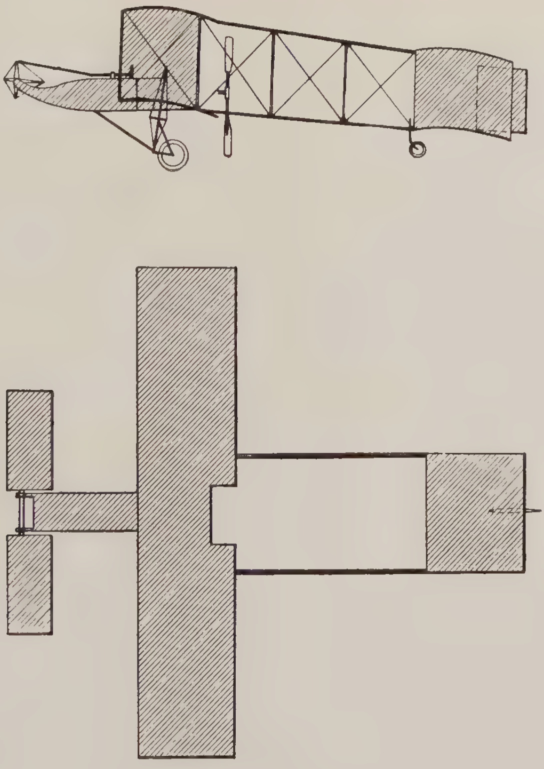


FIG. 98.—Drawings of the Voisin biplane.

diameter, and 4 feet 7 inches pitch, and has a central non-acting portion of about 2 feet 8 inches diameter. It is mounted directly upon the engine shaft, and runs at about 1100 revs. per minute.

The main planes are single surfaced, and have a camber of about 1 in 20.

The maximum rise is 2 feet from the front edge. The elevators are doubled surfaced. The weight in order of flight is about 1200 lbs.

The total supporting area is about 590 square feet,

FIG. 99.—The Voison machine "head on" in full flight at Rheims.

giving a load 2 lbs. per square foot of supporting surface. The gliding angle is between 1 in 6 and 1 in 7.

Figs. 99, 100, 101, and 102 show photographs of this famous machine in full flight under various conditions.

FIG. 100.—The Voisin machine from front right-hand side in full flight at Juvisy.

FIG. 101.—The Voison machine "broadside on" in full flight at Rheims.

FIG. 102.—The Voisin machine from rear right-hand side in full flight at Juvisy.

Farman

The type of machine, shown in Fig. 103, built by Farman, is a modification of the Voisin machine. It is a biplane, having a single elevator 15 feet by 3 feet in front, and a tail biplane in the rear. The ailerons (5 feet 9 inches by 1 foot 7 inches) are let into the outer portions of the rear edge of the main planes, and are pulled down against the action of the wind.

The main planes are 32 feet 6 inches span, by 6 feet 4 inches wide, by 6 feet 4 inches apart. The tail planes are 6 feet 9 inches span, by 5 feet 9 inches wide.

Weight in flying order = 1400 lbs.
Total supporting area = 532 square feet.

Weight supported per square feet = 2·6 lbs.
One propeller, 8 feet 6 inches diameter, driven by a 50 horse-power engine.

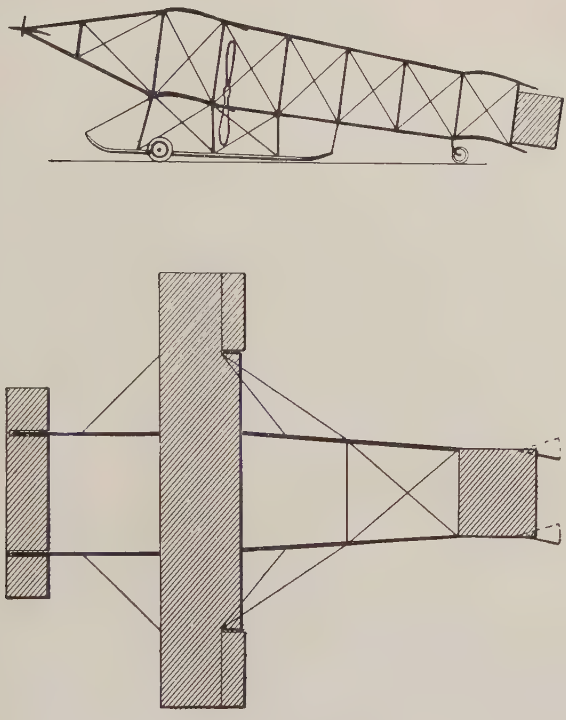


Fig. 103.—Drawings of the Farman machine.

The latest type of Farman machine is provided with a supplementary elevator at the back of the tail, thus giving the machine fore and aft control.

Monoplanes

Bleriot

M. Bleriot has been actively experimenting with monoplanes since 1900.

The Bleriot, No. 11 (cross-Channel) type (Fig. 104), consists of a front main plane, 28 feet span by 6 feet wide,

and a tail plane, 6 feet 1 inch by 2 feet 10 inches, having elevators 2 feet 10 inches square at each side. The camber of the main planes is 1 in 20. The machine is controlled laterally by warping the main plane, and it is steered by a vertical tail rudder, having an area of $4\frac{1}{2}$ square feet.

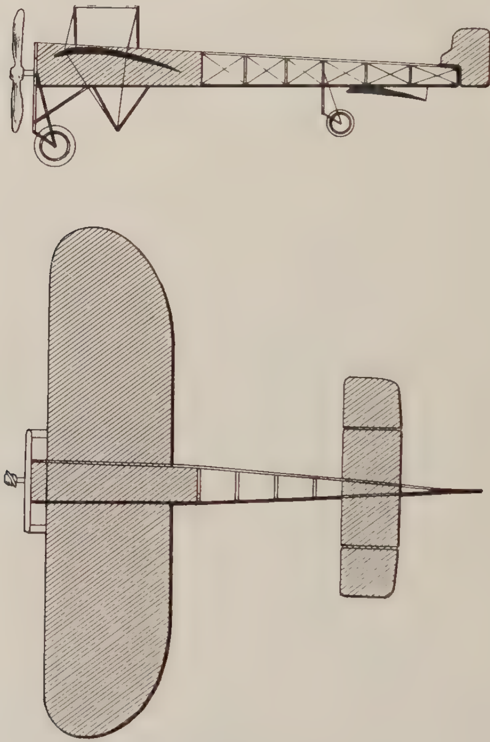


FIG. 104.—Drawings of the Bleriot monoplane. (No. II cross-Channel type.)

Weight in flying order = 715 lbs.
Total supporting area = 180 square feet.
Weight supported per square foot = 4 lbs.
The propeller is 6 feet 8 inches diameter, and is placed in front of the main plane, and is driven by an engine of 25-30 horse-power.

This machine is seen in full flight in Fig. 105.

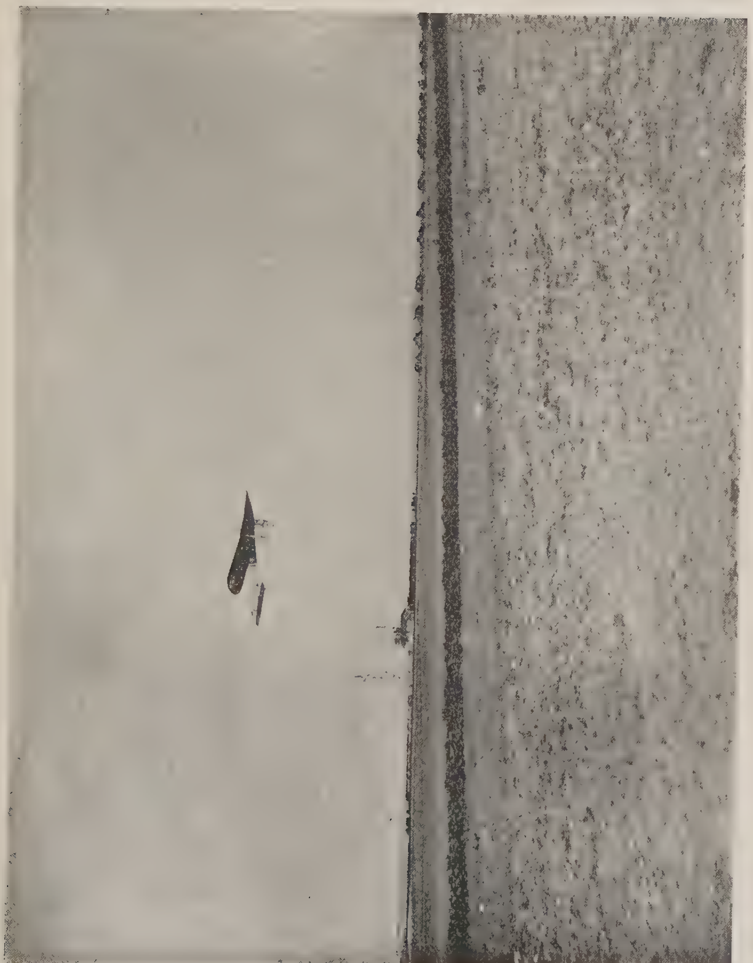


Fig. 105.—The Bleriot machine in full flight.

Antoinette

The main plane of this machine (Fig. 106) is formed of two wings set at a dihedral angle for the purpose of giving the machine lateral stability. The tail consists of an approximately triangular horizontal plane with the apex towards the main plane. It is surmounted by a triangular vertical plane which gives the machine additional lateral stability. The elevator consists of a triangular horizontal

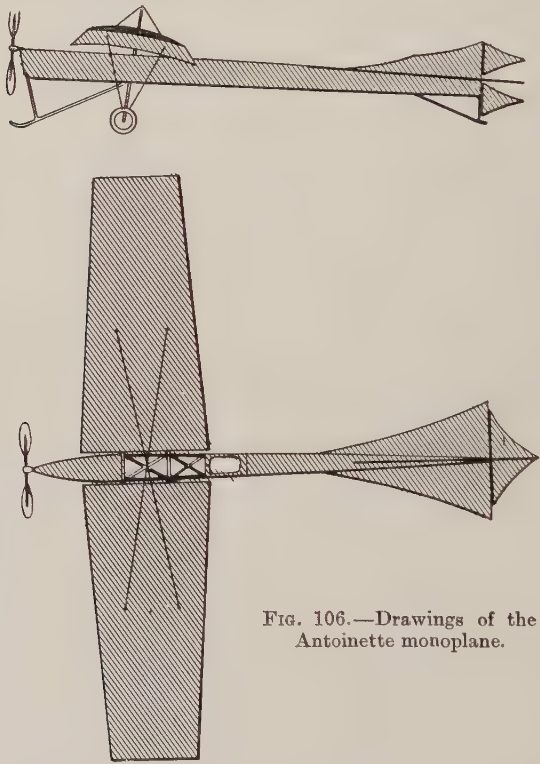


Fig. 106.—Drawings of the Antoinette monoplane.

plane placed behind the horizontal tail. The machine is steered by triangular vertical rudders. The main plane is 46 feet span, and is 10 feet wide at the centre, and 6 feet 8 inches at the tips. The machine is controlled laterally by warping the wings or by ailerons on the back edges.

Weight in flying order = 1300 lbs.

Total supporting area = 420 square feet.

FIG. 107.—Latham in full flight at Rheims on an Antoinette monoplane.

Weight supported per square foot = 3·1 lbs.
One propeller, 6 feet 10 inches diameter.

The machine is shown in Fig. 107 in full flight.

Santos-Dumont

In this machine (Figs. 108 and 109) the dimensions have been reduced to the smallest amount. Thus, the span is only 18 feet and the length over all 20 feet. The lateral stability is controlled by warping the wings, and the machine is steered and elevated by a cruciform tail mounted on a universal joint.

The main planes are 6 feet 5 inches wide, having a camber of 1 in 19.
Weight in flying order = 412 lbs.
Total supporting area = 140 square feet.
Weight supported per square foot = 2·94 lbs.
One propeller, 6 feet 6 inches diameter, driven by a 30 horse-power engine.

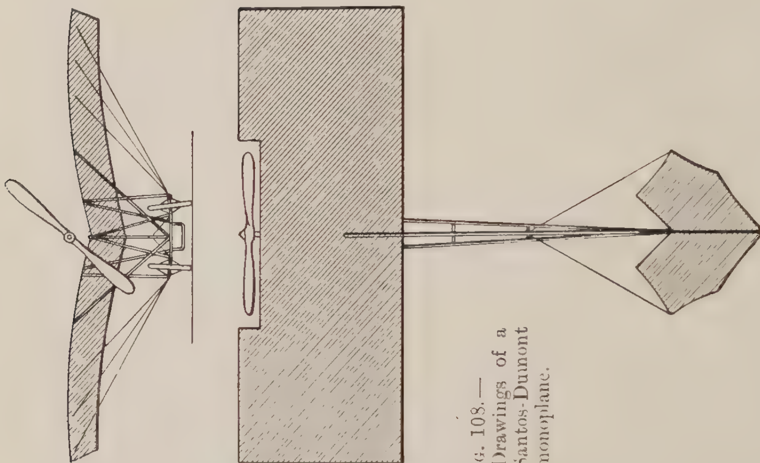


FIG. 108.—Drawings of a Santos-Dumont monoplane.

FIG. 109.—Santos-Dumont in full flight on his monoplane.

CHAPTER X

Aeronautical Engines

The problem of flight has been solved largely, owing to the light and powerful motor which has been developed for motor-car work.

Sixteen years ago, Sir Hiram Maxim, by utilising every appliance which experience could suggest, or modern skill could devise, was able to produce a steam-engine of 180 brake horse-power, which weighed only 320 lbs.

The total weight per horse-power of the whole apparatus, complete with burner, boiler, pump, condenser, etc., was reduced to the low value of between 8 and 9 lbs. per horse-power. This result was the best that had ever been done, and appeared marvellous at the time.

Sir Hiram soon found that the great disadvantage of the steam-engine was on account of the great quantity and weight of water which it consumed.

In a paper which he wrote at that time, he stated this difficulty, and said that what was required was to develop the gasolene motor. This was done for the motor-car, and as a result the air has been conquered.

Types

In the early days of the motor-car, many varied and different types of engine were proposed. These have nearly all died out, and the engine has been reduced to the most suitable type.

The standard type which is best suited for aeronautical work has not yet been determined. It is, therefore, our purpose to consider the various types which are in existence.

Aeronautical engines may be broadly divided into three types:—

(1) Modifications of the existing motor-car types.

(2) The radial type, in which the cylinders are disposed around or partly around the crank-case and shaft.

(3) The rotary type, in which the shaft is fixed and the cylinders revolve around it.

Cycle of Operations

Most petrol engines work on the cycle of operations known as the Otto cycle. In this cycle there is only one explosion for every four strokes or two revolutions.

(1) On the down or *suction stroke*, the inlet valve is opened, and the air and petrol are sucked into the cylinder.

(2) On the back or *compression stroke*, the mixture is compressed.

(3) At the end of the compression, it is exploded by means of an electric spark. Then follows the *expansion* or *working* stroke.

(4) On the back or *exhaust stroke*, the exhaust valve is open, and the exploded products are exhausted.

Ignition

In almost all flying-machine engines, the ignition is obtained by means of a high-tension magneto. The principle of this is the same as that of the electro-magnetic machine, or dynamo.

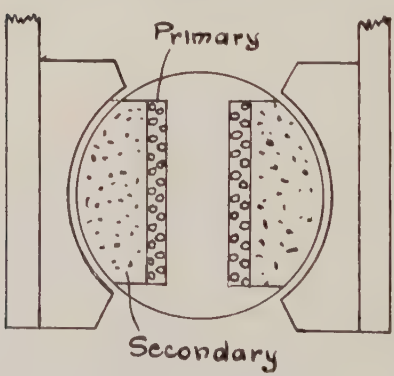


Fig. 110.—Diagram illustrating the principle of the high-tension magnet.

An armature, wound with a primary or low-tension winding, and a secondary or high-tension winding, is rotated between the poles of a permanent magnet. The armature consists of an iron core, wound, as shown in Fig. 110.

As the armature is revolved, the numbers of the lines of force passing through the core are varied, and thus an electro-motive force is generated in the

primary circuit, which causes a current to flow. This current is suddenly broken by means of the contact breaker, and this induces a current of high potential in the secondary circuit, from which it is led away to the distributer connected to the sparking plugs.

PETROL

Commercial petrol is a mixture of various lighter liquids of the paraffin series, which have the chemical formula of the order of $C_n H_{2n+2}$.

Commercial petrol, having a specific gravity of ·72 at 15° C., is composed principally of a mixture of hexane and heptane—C_6H_{14} and C_7H_{16}.

The lightest petrol or gasolene supplied, having a specific gravity of about ·64, is composed almost wholly of pentane—C_5H_{12}. This very light petrol is now being used for flying machines. It will be seen from its chemical formula that it contains more energy per lb. weight than the others, owing to the increased proportion of hydrogen.

	* Spec. Gravity at 15° C.	Coef. of Expansion. (a)
Pratt	·719	·00125
Shell (ordinary) ...	·721	·00121
Carless	·704	·00131
Pentane	·63	·00155
Hexane	·68	·00133
Heptane	·736	·001

The density d_t at any temperature t is given by the expression

$$d_t = d_{15}[1 - a(t-15)].$$

Now, although petrol is a highly volatile and inflammable liquid, it only forms an explosive mixture with air between narrow limits. It is a difficult thing to get just the right mixture for an explosion at atmospheric pressure. Fortunately this range is increased by compression, nevertheless, it is essential that a motor should be supplied with the right mixture under all conditions.

There have been many schemes for increasing the range.

* The thermal and combustion efficiency of a four-cylinder petrol motor. "Proceedings of Institution of Automobile Engineers," 1909.

They have all been found impracticable, or too expensive. The only practical method of increasing the range is by compressing the mixture.

* Fig. 111 shows the ratio of air to petrol, plotted against the thermal efficiency of an engine having a com-

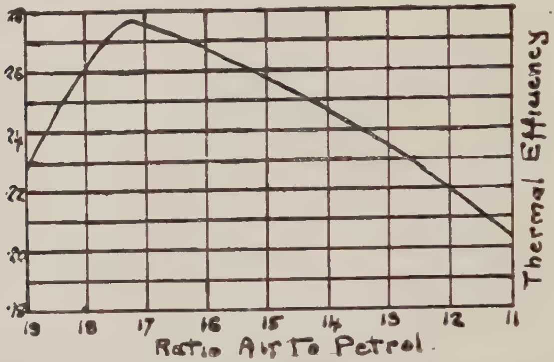


FIG. 111.—Curve of the ratio air to petrol, plotted against thermal efficiency. (Watson.)

pression of about 85 lbs. per square inch. It will be seen that, for a reasonable efficiency of ·24 and over, the mixture may only be varied between $\frac{13·5}{1}$ and $\frac{18·5}{1}$.

THE RELATION BETWEEN THE HORSE-POWER AND THE SIZE OF AN ENGINE

An aeroplane motor must be (1) light, (2) efficient, (3) reliable, (4) automatic in its action.

With regard to the first point, it is interesting to investigate the relation between the horse-power and the size of a motor.

The following reasoning is due to Mr Lanchester.† One of the determining factors of the horse-power developed by an engine is the revolution speed. This limit is fixed by the strength of materials; we must, therefore, introduce the stress s into any equation we may form. Since different materials may be used, we must also introduce the density d. The horse-power will also vary as

* "Proceedings of Institution of Automobile Engineers," 1909.
† *Ibid.*

some power of a linear dimension, hence, we must introduce L.

Hence, we may write—

$$\text{H.P.} = L^p \times d^q \times s^r.$$

Now, using the principle of dimensions, we get

$$\text{Velocity} = \frac{\text{length}}{\text{time}} = \frac{L}{T}$$

$$\text{Acceleration} = \frac{\text{velocity}}{\text{time}} = \frac{L}{T^2}$$

$$\text{Force} = \text{mass} \times \text{acceleration} = \frac{M\,L}{T^2}$$

$$\text{Work done} = \text{force} \times \text{distance} = \frac{M\,L^2}{T^2}$$

$$\text{Power} = \frac{\text{work done}}{\text{time}} = \frac{M\,L^2}{T^3}$$

$$\text{Density} = d = \frac{\text{mass}}{\text{volume}} = \frac{M}{L^3}$$

$$\text{Stress} = s = \text{force per unit area} = \frac{M\,L}{T^2\,L^2} = \frac{M}{L\,T^2}.$$

$$\therefore \frac{M\,L^2}{T^3} = L^p \times \frac{M^q}{L^{3q}} \times \frac{M^r}{L^r\,T^{2r}}$$

Whence—

$$\left.\begin{aligned} q + r &= 1 \\ 2r &= 3 \\ p - 3q - r &= 2 \end{aligned}\right\} \text{ giving } \left\{\begin{aligned} r &= 1{\cdot}5 \\ q &= -{\cdot}5 \\ p &= 2 \end{aligned}\right.$$

$$\therefore \text{H.P.} = \frac{s^{1\cdot5}}{d^{\cdot5}} \times L^2 \times \text{constant}.$$

From this we see that—

(1) The power varies as the *square of the linear dimension.*

(2) If the basis of measurement be the bore and the stroke, the rating measurement may be the product of their fractional powers, provided the sum of their indices $= 2$, *i.e.*, so that the product shall be of the dimension L^2. Thus, if $D =$ diameter, and $S =$ stroke, then the rating measurement may be DS, $D^{1\cdot5}S^{\cdot5}$, or $D^{1\cdot1}S^{\cdot9}$, or generally D^nS^{2-n}.

(3) The weight per horse-power of an engine of similar design varies *inversely as the linear measurement*. This is most important. Thus, a four-cylinder engine with 5-inch by 5-inch cylinders, is but *one-half* the weight of a single-cylinder engine of the same power, *i.e.*, 10-inch diameter and stroke.

As a result of Mr Lanchester's reasoning, we see that we can decrease the weight per horse-power by increasing the number of cylinders. Hence, we may look for a greater increase in the number of cylinders of aerial engines than in the case of motor engines. As a set-back to this, it should not be forgotten, however, that the efficiency increases with the size of the engine, *i.e.*, a large engine is more efficient thermally than a small one. As the weight of fuel carried is thus introduced into our equations, the increase in the number of cylinders will be limited by this factor.

The horse-power of a petrol engine may be rated by the following formula:—

(1) Royal Automobile Club. $\frac{D^2 n}{2{\cdot}5}$.

(2) Displacement rating. Total volume displaced by piston per minute ÷ 10,000.

(3) Mr Lanchester. $4n\,D^{1{\cdot}6}\,s^{{\cdot}4}$.

Where D = diameter, S = stroke, and n = No. of cylinders.

Dr Hele-Shaw has plotted all the horse-powers of aeroplane motors, and, as a result, he suggests as a modification of the R. A. C. formula, $\frac{D^2 n}{2}$ as a rating for aeroplane motors.

In deducing the horse-power of a petrol-engine, it may be assumed that the piston speed is about 1000 ft. per minute, and the M. E. P. 70 lbs. per square inch.

How the Weight has been Reduced

The weight of a petrol-motor has been reduced by various means, such as:—

(1) By increasing the number of cylinders.

(2) Placing the cylinders radially, so as to reduce the length and weight of crank-case.

(3) Forming the cylinders of turned and very thin steel tube.
(4) Using spun metal, or electrolytically-deposited jackets.
(5) Designing the engine so as to be independent of a fly-wheel.
(6) Using the highest-grade materials with increased machining, and a general attention to design.
(7) In some cases, combined inlet and exhaust valves are used.

The Modified Motor-car Type

Wolseley

The principal consideration in the design of this engine was to secure the utmost reliability and the maximum

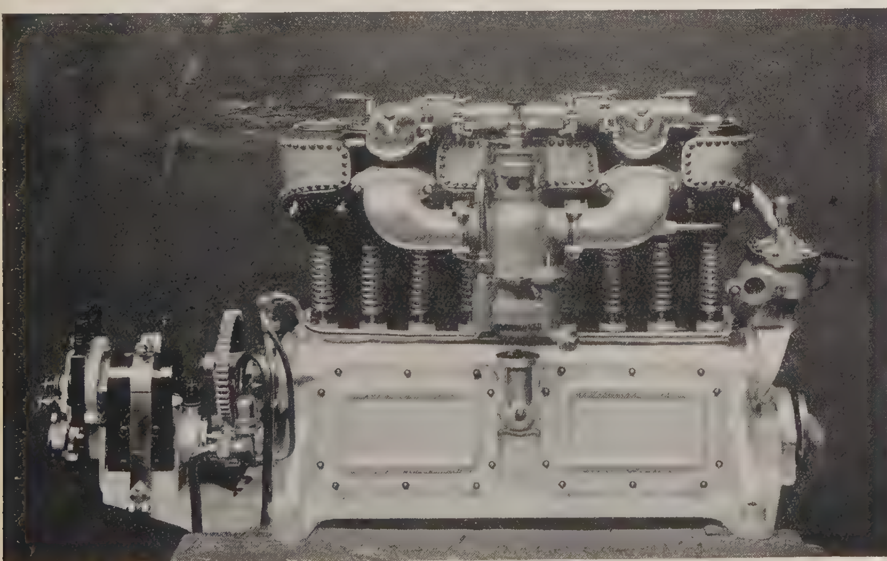


Fig. 112.—Wolseley engine, 30 horse-power.

reduction of weight consistent with reliability. An engine has thereby been produced, which, although not being quite so light as some engines on the market, can be relied upon to work for long periods at full load. This engine

has been used with great success by Madame de la Roche, the first lady aviator, who has made some splendid flights both alone and with a passenger.

The Wolseley engine is made in two types:—

(1) 30 H.P. four-cylinder, weight 180 lbs.
(2) 60 H.P. eight-cylinder, V engine.

(1) The 30 horse-power engine (Fig. 112) has four

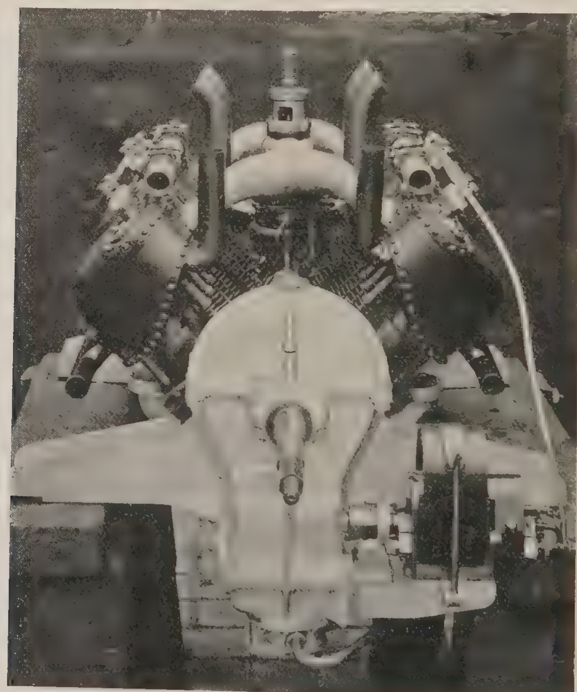


FIG. 113.—Wolseley engine, 60 horse-power.

cylinders of $3\frac{3}{4}$-inch. bore by $5\frac{1}{2}$-inch. stroke. The valves are underneath, and all on the same side of the motor, and are all operated from the cam-shaft by hardened steel tappets. The cooling is effected by means of a gear-driven centrifugal pump. The ignition is of the Bosch-Dual system. The cylinders are of close-grained cast iron, cast in pairs with their heads and liners, and ground to gauge. The water-jackets are made of sheet metal

secured by a number of screws, or stud bolts. The crank-shaft is carried by three bearings. The connecting rods are of steel, with the big ends of phosphor-bronze white-metalled.

The engine gives 30 brake horse-power at 1100 revs., and 37 brake horse-power at 1400 revs. per minute, or 5·7 lbs. per brake horse-power.

(2) The 60 horse-power engine (Fig. 113) has eight cylinders set at an angle of 90° in V fashion. The cylinders are, as before, $3\frac{3}{4}$-inch bore and $5\frac{1}{2}$-inch stroke. The *valves* are underneath and on the inside, and are operated from a central cam-shaft by means of rockers. The *carburettor* is mounted in the centre of the engine to secure short induction pipes and an equal distribution to the cylinders. The *cooling* is by thermo-syphon, or pump. The engine is *lubricated* by means of a gear-driven pump which positively forces oil to all main bearings and connecting rods. The other details are as before.

The total weight is 340 lbs. complete, including fly-wheel. Total brake horse-power 75, or 4·6 lbs. per horse-power. The propeller may be driven directly from the main shaft, or by means of gearing at cam-shaft speed.

The Green Engine

The cylinders of this engine (Figs. 114 and 115) are of cast steel turned inside and out. The water-jacket is of thin copper, No. 22 gauge, pressed from the solid and made water-tight at the bottom by means of an india-rubber ring sprung into a circular groove turned in the cylinder. This ring is not affected by the heat of the cylinder.

The exhaust and inlet valves are mounted in removable cages. The jacket is made water-tight by means of external locking rings, and the valve cages are secured by internal locking rings. The valves are operated from an overhead cam-shaft by rocking levers which are pivoted inside transverse extensions of the aluminium cam-shaft case. For detaching a valve, the cam-shaft case may be swung out of the way by undoing two clamping-screws. The cylinders are bolted directly to the bearings. The lower end of the crank-case is formed of sheet aluminium with an oil pump in the middle. The lubricating oil is

forced by means of a gear-pump to the main oil-channel, cast solid with the crank-case. It is taken from here through leads to the hollow columns through which the bolts pass, and thence to the main bearings and hollow crank-shaft. The cam-shaft is worm-driven from a vertical shaft, which is in turn worm-driven from a half-speed shaft.

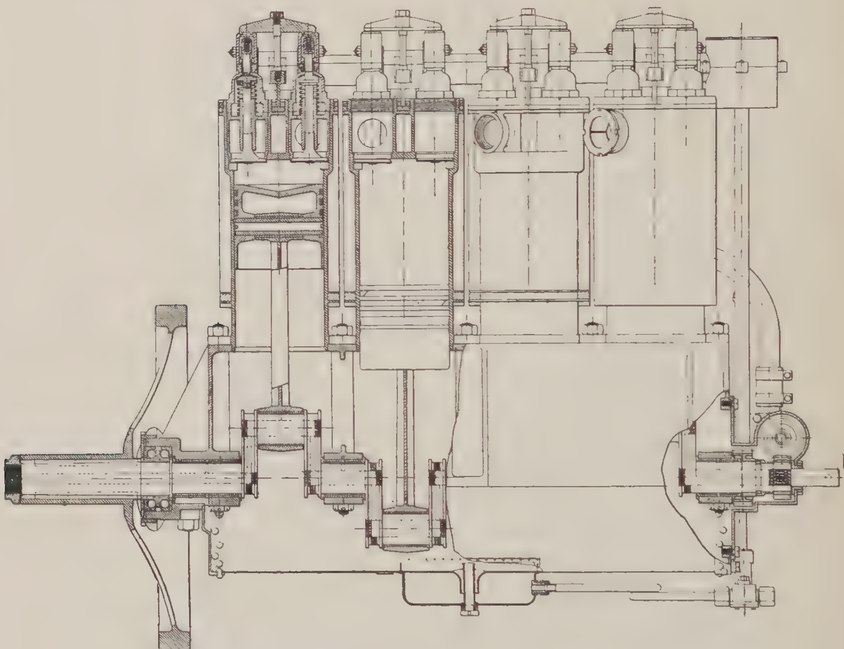


FIG. 114.—Green engine. Longitudinal part. Sectional elevation.

The engine is made in two types :—

(1) 30-35 H.P. four-cylinder vertical engine.
(2) 60 B.H.P. eight-cylinder V type, weight 246 lbs.

(1) Some recent tests of the 30-35 H.P. engine are as follows :—

30 H.P. at 1100 revs. per min. ;
34 H.P. at 1150 revs. per min. ;
36 H.P. at 1175 revs. per min.,

45 B.H.P. was obtained. With a 23½-lbs. fly-wheel, the

engine could be run at 290 revs. per min. Upon being accelerated, the revolutions increased to 3000 per min.

Cylinders.—105 m/m × 120 m/m.

Weight.—With petrol, oil, and water pipes and carburettor, 155 lbs.; fly-wheel, 23½ lbs.; or 3·44 lbs. per B.H.P.

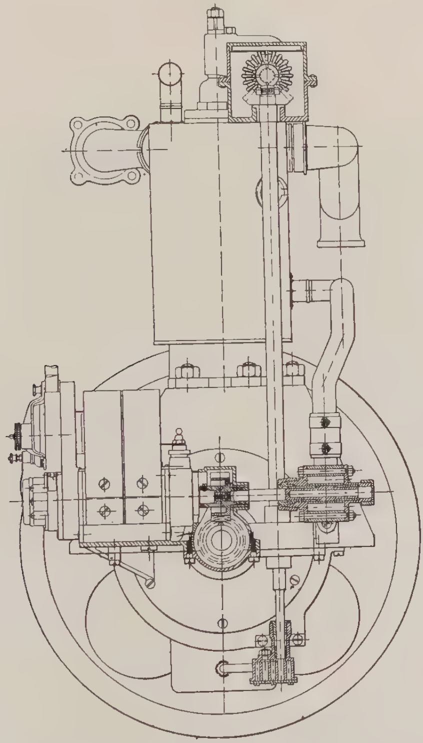


FIG. 115.—Green engine. End elevation.

Carburettor. — Non-float automatic type. It is unaffected by variation of the angle, and will work as efficiently in an inverted as in a horizontal position. Weight, 18 ozs.

(2) 50-60 H.P. engine.

50 H.P. at 1050 revs. per min.

60 H.P. at 1150 revs. per min.

Maximum, 70 B.H.P.

Cylinders.—4, 140 m/m × 146 m/m.
Weight.—As above, 260 lbs.; fly-wheel, 37 lbs.
Carburettor.—As above. Weight, 24 ozs.
Weight per B.H.P., 3·7 lbs.

Wright Engine

This engine (Fig. 116) is now made by Messrs Bariquand & Marre.

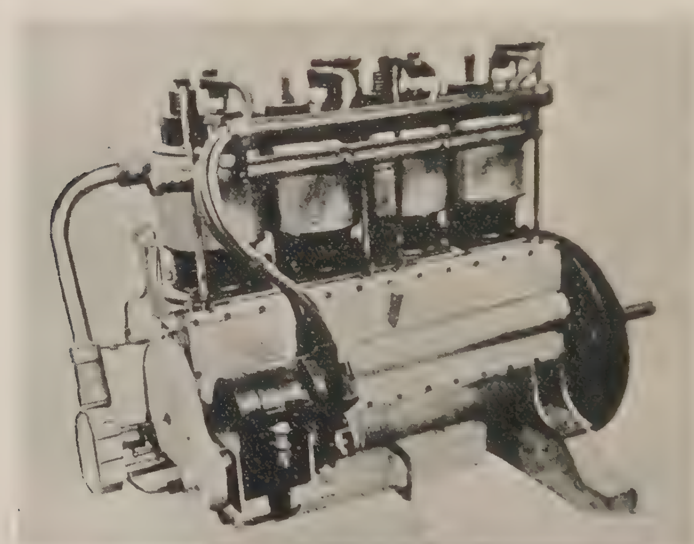


Fig. 116.—Wright engine.

Four cylinders, of cast steel, 112 m/m bore × 100 m/m stroke.

Weight, 96 kilos, or 211 lbs.

30 B.H.P. at 1300 revs. per min., *i.e.*, 7 lbs. per H.P.

Water-jackets of aluminium tubes, held in place by shrunk steel rings.

Pistons are of steel.

Forced lubrication.

There is no carburettor. The petrol is pumped directly into the engine.

Ignition, high tension Eiseman.

Radiator, plain flat copper tubes vertically placed between the main planes.

Exhaust ports are provided at the end of the stroke.

Antoinette Engine

Generally eight cylinders, V type, 50 horse-power (Fig. 117); sixteen and thirty-two cylinders have been made.

Cylinders of steel in one piece, forged solid with the head and valve casings. The two rows of cylinders are

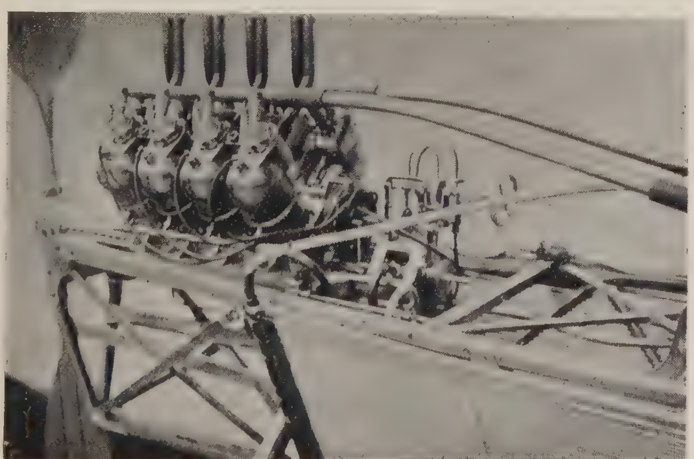


FIG. 117.—Antoinette engine.

slightly offset to allow the connecting rods of opposed cylinders to engage the same crank-pin.

The petrol is pumped directly into the engine.

Jackets are of electrolytically-deposited copper. The water is boiled in these jackets and is condensed in a large aluminium tube condenser. It is returned by a small belt-driven pump.

Exhaust valves only are mechanically operated.

Curtiss Engine

This engine (Fig. 118) won the first Aerial Gordon-Bennett race.

Four cylinders, cast and turned $\frac{5}{32}$-inch thick. Copper jackets fastened in place by welded joints.

Bosch high-tension magneto.

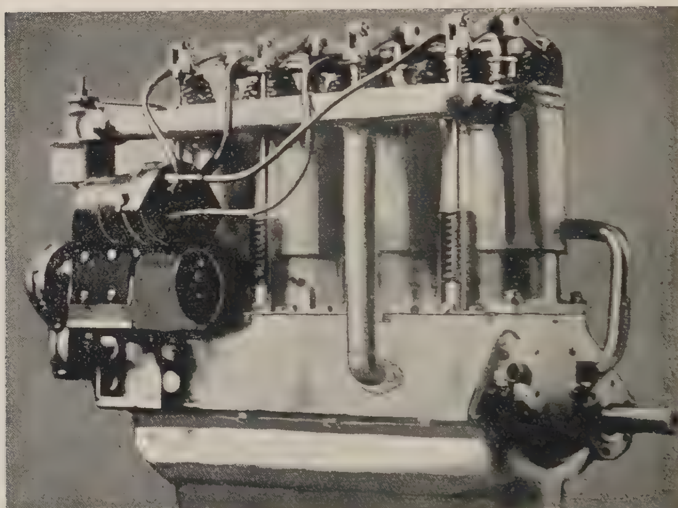


FIG. 118.—Curtiss engine.

30 H.P. at 1200 revs. per min.
Weight, with magneto, 97½ lbs. Radiator, 40 lbs.
Weight per B.H.P. = 3·24 lbs.

Pipe Engine

The engines which we have so far considered, have been water-cooled. An example of an air-cooled engine is the Pipe (Figs. 119 and 120).

Eight cylinders, V fashion, enclosed in an aluminium box. Air drawn across ribbed cylinder.

The exhaust and inlet valves are combined, one working within the other.

The cam-shaft and the crank-shaft are mounted on ball bearings.

Opposed cylinders are staggered, as in the Antoinette.
50 H.P. at 1200 revs. per min.
70 H.P. at 1950 revs. per min.
Cylinders, 100 m/m bore × 100 m/m stroke.

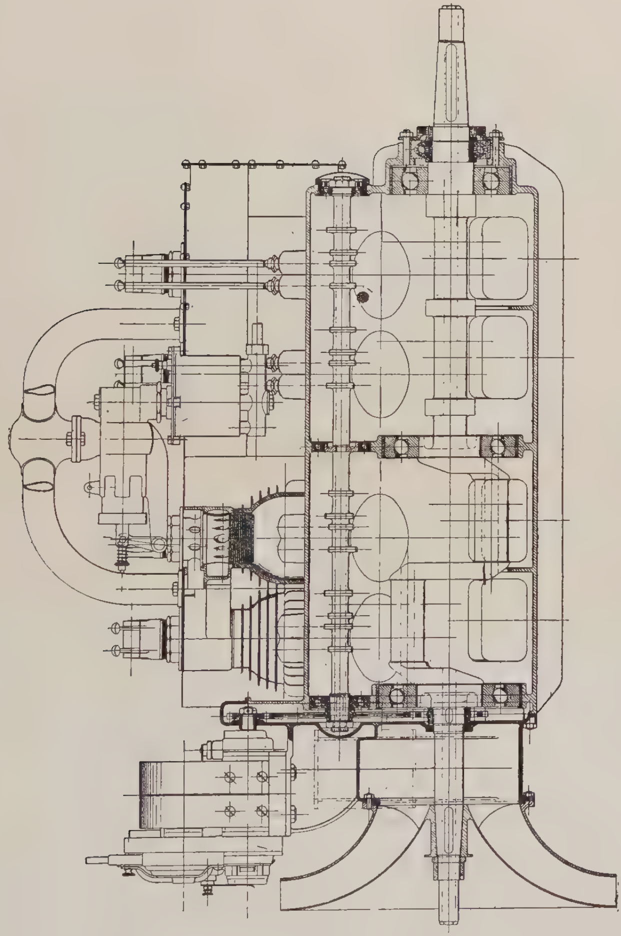


Fig. 119.—Pipe engine. Longitudinal part. Sectional elevation.

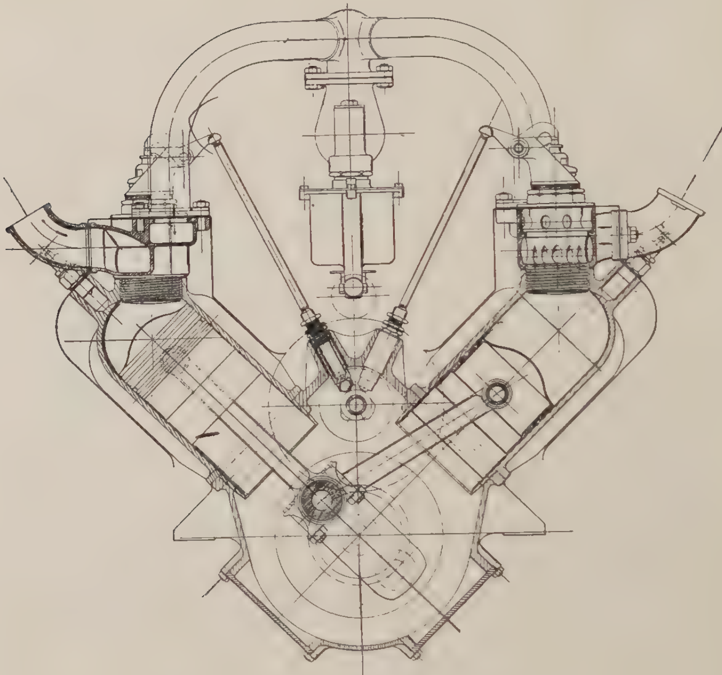


FIG. 120.—Pipe engine. End elevation.

Maxim Engine

This engine (Fig. 121) is of the four-cylinder vertical type, 5-inch. diameter by $5\frac{5}{8}$-inch. stroke. The total weight, with circulating pump, magneto and oil pump, is 220 lbs. It has developed 87 B.H.P. at 1400 revolutions, with a petrol consumption of 0·6 lbs. per B.H.P. per hour. The cylinders, pistons, connecting-rods and crank-shaft are of a special brand of Vickers steel, having a tensile strength of 57 tons and an elongation of 14 per cent. The water-jackets are of German silver, $\frac{1}{32}$-inch thick.

Lubrication.—The piston of the lubricating pump is lifted slowly by the engine through a train of gear-wheels against the action of a strong spiral spring. When a cam releases the spring, the piston is forced suddenly downwards under great pressure, and thus the oil is forced periodically to every part of the engine. The petrol

tank is under the engine, and the petrol is fed to the carburettor at a pressure of about 4 lbs. to the square inch.

Carburettor.—The carburettor consists of two concentric tubes, the inner one of which is perforated. Inside the inner tube is mounted a piston, consisting of two discs spaced apart by a small perforated tube. This piston

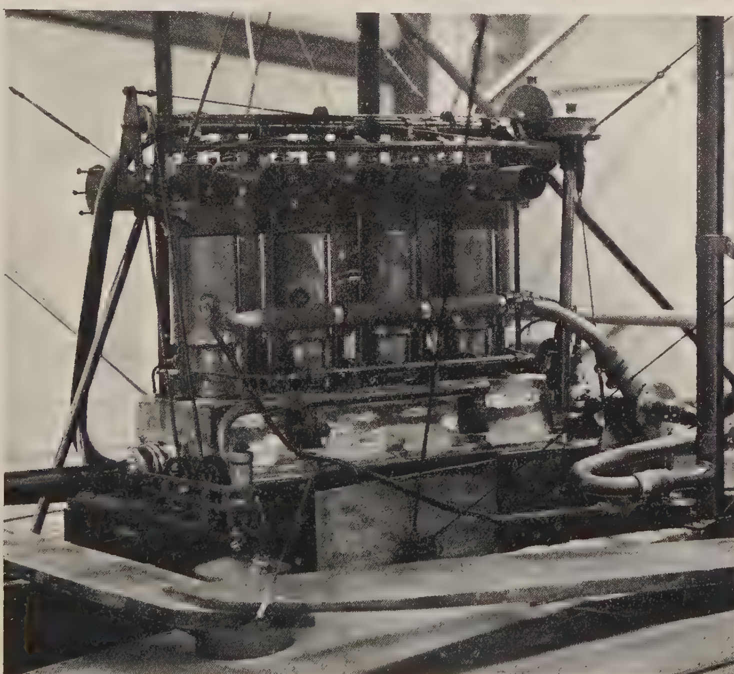


FIG. 121.—Maxim engine.

corresponds with the float of the ordinary carburettor, and carries the float needle, which is so arranged that the higher the float lifts, the greater is the opening to petrol. The upper disc acts as a dashpot and the lower one, as it rises, opens the ports to air and closes them to petrol. Thus, when the engine is running slowly, all the air is drawn through the spray chamber; but when it is running fast, and a good mixture is easily obtained, some of the ports are directly opened to the air.

Radial Type

In the radial type, the explosions should take place at equal intervals to prevent fluctuations in the torque.

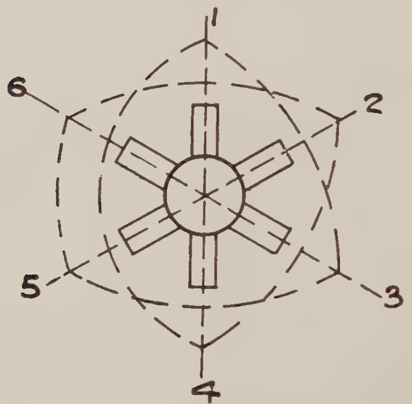


FIG. 122.—Diagram illustrating the order of firing the cylinders of radial engines.

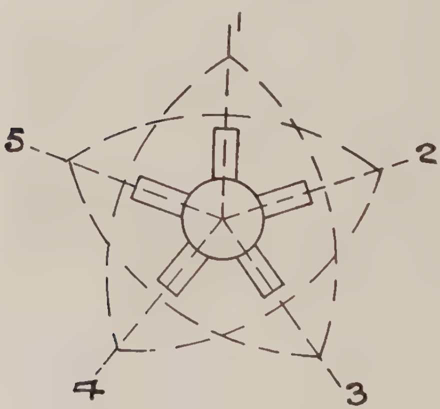


FIG. 123.—Diagram illustrating the order of firing the cylinders of radial engines.

If there is an even number of cylinders, then, since all the cylinders must explode in two revolutions, we can explode in order 1, 3, 5, 6, 2, 4, 1, etc. (Fig. 122). We thus get a short gap between 5 and 6 and a long gap between 1 and 4.

With an odd number of cylinders, we can explode 1, 3, 5, 2, 4, 1, etc. (Fig. 123), and thus there are equal intervals between the explosions.

In some engines, such as the R.E.P., all the cylinders below the line AB are placed above the crank-case behind the cylinders 1, 2, 5. This simplifies the lubrication, but does not alter the principle of the engine.

In some radial engines, the lubrication difficulty is overcome by placing the cylinders horizontal.

Rotary Type

In the radial rotary engine, the crank is fixed and the cylinders revolve. The most noted engine of this type is the Gnome (Fig. 124).

It has seven steel cylinders turned from the solid and connected to the crank-case by means of a groove and split ring.

The exhaust valves are in the head, and the inlet valves are balanced and are in the pistons (Fig. 125).

FIG. 124.—The Gnome engine.

The connecting rods are gudgeoned to pieces which screw into the pistons. One of the connecting rods—"the master"—embraces the crank-pin, and the other connecting rods are pivoted to the enlarged head of "the master."

The lubricating oil and petrol are supplied to the crank-case.

By revolving the cylinders in this way, the difficulty of satisfactory air-cooling is entirely overcome.

There is one great objection, however, to revolving the

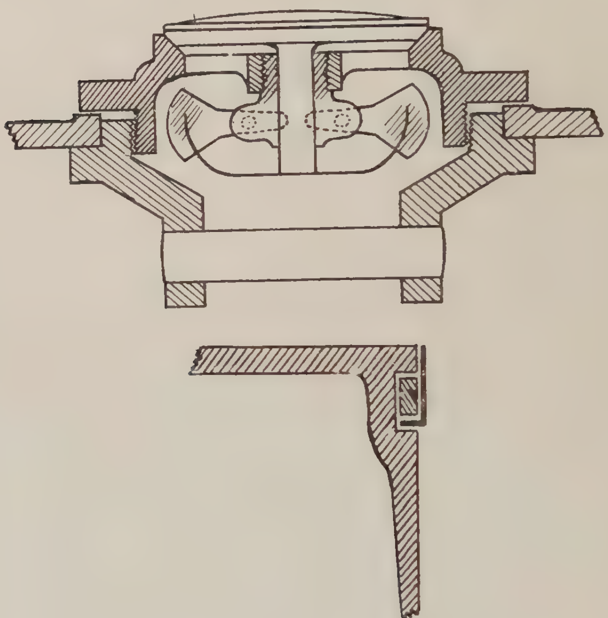


Fig. 125.—Details of Gnome engine.

cylinders, which is additional to any mechanical difficulties, and that is due to the resistance. This resistance is a serious consideration.

Special Machinery for Manufacturing Aerial Engines

Doubtless, as the demand for aerial engines increases, the prices will be reduced by standardising the various parts and manufacturing them by special machinery. Fig. 126 shows such a machine, designed and constructed by Alfred Herbert, Ltd., Coventry, for turning out Gnome cylinders at high speed. The steel ingot, weigh-

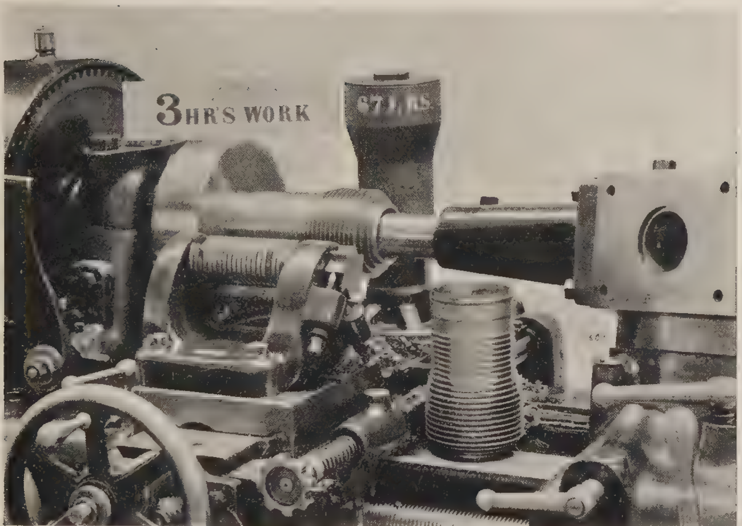


FIG. 126.—Lathe for turning Gnome cylinders at high speed.

ing 67 lbs., is reduced to the completed cylinder, weighing 5 lbs. 5 ozs., and a boss is welded in position in three hours.

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